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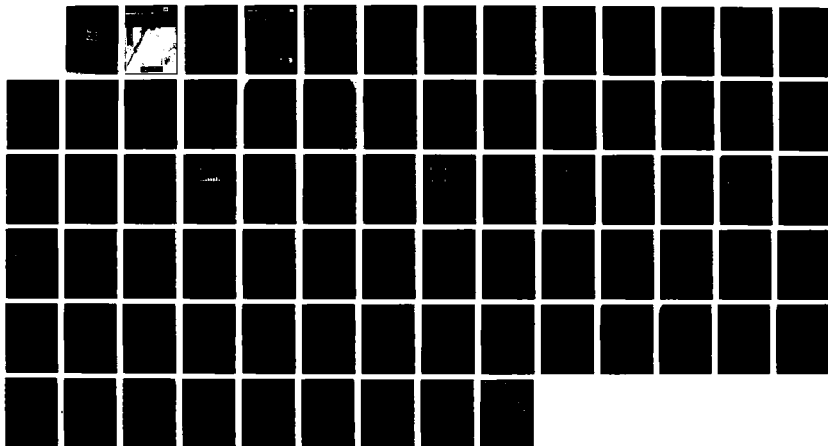
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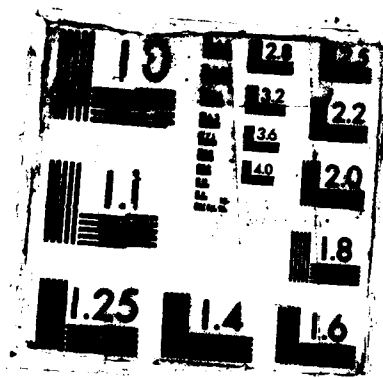
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## REPORT 87-8

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### *Use of Landsat digital data for snow cover mapping in the Upper Saint John River Basin, Maine*

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***Cover: Landsat MSS image (scene ID E-30672-14443-5) acquired during the 1979-80 season for the Upper St. John River Basin.***

# CRREL Report 87-8

June 1987



## *Use of Landsat digital data for snow cover mapping in the Upper Saint John River Basin, Maine*

Carolyn J. Merry and Michael S. Miller

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6a. NAME OF PERFORMING ORGANIZATION U.S. Army Cold Regions Research and Engineering Laboratory		6b. OFFICE SYMBOL (If applicable) CRREL		7a. NAME OF MONITORING ORGANIZATION Office of the Chief of Engineers	
6c. ADDRESS (City, State, and ZIP Code) Hanover, New Hampshire 03755-1290				7b. ADDRESS (City, State, and ZIP Code) Washington, D.C. 20314-1000	
8a. NAME OF FUNDING / SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code)				10. SOURCE OF FUNDING NUMBERS	
		PROGRAM ELEMENT NO.		PROJECT NO.	TASK NO.
				WORK UNIT ACCESSION NO. CWIS 31584	
11. TITLE (Include Security Classification) Use of Landsat Digital Data for Snow Cover Mapping in the Upper Saint John River Basin, Maine					
12. PERSONAL AUTHOR(S) Merry, Carolyn J. and Miller, Michael S.					
13a. TYPE OF REPORT		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) June 1987	
				15. PAGE COUNT 74	
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Hydrologic modeling		
			Landsat		
			Remote sensing		
			Runoff		
			Snow cover		
			Snow water equivalent		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) Measurements of snow depth and its water equivalent were obtained at 11 snow courses in the Allagash, Maine, area in conjunction with the acquisition of five Landsat-2 and -3 images during the 1977-78 and 1978-79 winters. To test a hypothesis that Landsat reflected radiance values on a regional scale do change, histograms of the Landsat MSS band 7 reflected radiance values for a 300-x-300-pixel (420 km <sup>2</sup> ) area near Allagash were evaluated to quantify the change. A statistical description (skewness and kurtosis) of the histogram for each scene was developed and then correlated with ground measurements of snow depth. A snow index based on skewness and modal population was found to correlate well with snow depth. Following these initial results, the Landsat data were re-examined and corrections were made for solar elevation and MSS sensor calibration. The reflected radiance from open areas showed a consistent increase in intensity with increasing snow depth. The forested land cover classes did not change with snow depth. Digital imagery data acquired on 31 May 1978 when the land was snow-free was used to classify land cover categories. Ground truth measurements of water equivalent of the snow cover were area-weighted using the land cover classification to derive regional values on each of the five Landsat winter scenes. The					
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS				21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Merry, Carolyn J.				22b. TELEPHONE (Include Area Code) 603-646-4100	
				22c. OFFICE SYMBOL CRREL-RE	

19. Abstract (cont'd)

1 March 1978 snow measurement of 19.46 cm of water equivalent was used as an input value to the SSARR model. The SSARR prediction for the 1 March-31 May 1978 ~~time~~ period was within 78% of the measured runoff for the initial baseflow period and within 66% measured for the spring melt recession period. However, the timing of six observed runoff peaks was off by 2 to 9 days. The magnitude of five of the predicted runoff peaks was within 75% of the recorded streamflow. Additional work on calibrating the basin peak timing and melt rate factors is required.

*Keywords: Hydrologic modeling.*

## **PREFACE**

This report was prepared by Carolyn J. Merry, Research Physical Scientist, Geological Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory, and Michael S. Miller, M/A-COM Sigma Data Inc., Goddard Institute for Space Studies.

The study was sponsored under the Corps of Engineers Civil Works Remote Sensing Research Program, CWIS 31584, *Snow Cover Analysis Using Landsat Digital Data*.

The authors express their appreciation to Dr. Harlan L. McKim for his support and helpful technical discussions on the project; to Saul Cooper (formerly Chief, Water Control Branch, U.S. Army Engineer Division-New England) and Dr. Jerry Brown for their support throughout the project; to Roy Bates (CRREL), to Mary-Lynn Brown (CRREL) and Lenora Wong (formerly with U.S. Air Force Academy) for assistance in reduction of the meteorological and snow course data; to Judy Karen (formerly with Dartmouth College) and Nancy H. Humiston (CRREL) for computer input of certain data files; to Roy Gardner for his invaluable assistance in making the snow courses in conjunction with the Landsat satellite overpasses; to Roy Bates and Harold O'Brien (CRREL) for their assistance in selecting the snow course sites and for technical review of this report; to Gary DeCoff (CRREL) and Jeffrey W. Doyle (Dartmouth College) for their work in adapting the SSARR model to run on a PRIME 400 computer; to Timothy Pangburn for his technical assistance when running the SSARR model; to Lawrence W. Gatto and Richard K. Haugen for technical review of earlier results from this project; and to Dr. Stephen G. Ungar (NASA GISS) and the GISS programming staff for development of the Landsat computer algorithms used in the analysis of the Landsat digital data.

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# Use of Landsat Digital Data for Snow Cover Mapping in the Upper Saint John River Basin, Maine

CAROLYN J. MERRY AND MICHAEL S. MILLER

## INTRODUCTION

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), along with the U.S. Army Engineer Division, New England (NED), have been involved in the Landsat data collection system and Landsat imagery analysis since the launch of ERTS-1, now known as Landsat-1, in July 1972 (Cooper et al. 1975). During the Landsat-1 experiment, CRREL participated in the data collection system studies by developing sensor interfaces for the Landsat data collection platforms (DCPs) and evaluating the system performance of various DCP installations. During the Landsat-2 program (1975-77), CRREL was involved in the digital processing of the Landsat computer-compatible tapes (CCTs) and in DCP sensor and software interface development. The hydrologic parameters selected for Landsat digital analysis were snow cover and delineation of wetlands and flooded areas (Merry and McKim 1978). This report summarizes the continuation of the Landsat program, with funding from the Office of the Chief of Engineers, from the winter of 1977-78 through the 1979-80 winter season.

Each spring the SSARR (Streamflow Synthesis and Reservoir Regulation) model is used to forecast snowmelt and precipitation runoff in the Upper Saint John River Basin in northern Maine. There are two ways to input snow to the SSARR model: one is to input the percentage of the watershed area covered by snow, and the second is to input a basinwide average value of water equivalent. However, present methods of using point snow course measurements to calculate a basinwide mean snow-water equivalent value can provide erroneous data because of nonrepresentative snow courses and inappropriate extrapolation methods.

Because of the remoteness of the area, it would be very costly to establish a data collection network for evaluating the water equivalent of the snowpack each year. However, estimates of the amount of water available in the snowpack are required for flood control during spring runoff.

There were two objectives for this study. The first objective was to analyze the Landsat digital data to determine if there is a correlation between snow depth and the measured intensities in the four spectral bands. The second objective was to determine how satellite multispectral data can be used in the SSARR model. The areal distribution of mapped land cover categories was area-weighted using snow course measurements that allowed a basinwide value of water equivalent to be calculated for each land-cover category. This estimate of snow-cover water equivalent was input to the SSARR model and compared to recorded stream flow measurements.

## BACKGROUND

### Literature review for remote sensing of snow cover

Barry (1983) conducted a survey of recent advances in selected areas of snow and ice research from 1979 to 1982. Results obtained by new measurement techniques and the application of remote sensing methods were described.

Manual methods have been used to delineate the areal extent of snow and the mean altitude of the snowline from Landsat Multispectral Scanner Subsystem (MSS) photographic data products (Meier 1973, 1975a; Barnes and Bowley 1974; Rasmussen and Ffolliott 1979, Bowley et al. 1981). The Landsat MSS imagery is available for a

185-km square area in four spectral regions (two visible bands of 0.5–0.6  $\mu\text{m}$  and 0.6–0.7  $\mu\text{m}$ , and two near-infrared bands of 0.7–0.8  $\mu\text{m}$  and 0.8–1.1  $\mu\text{m}$ ). Attempts were made to estimate the snow depth from Landsat MSS visible band imagery. Snow depths of 2.5 cm or more can be mapped reliably: it was found that the brightness level increases with an increase of the snow thickness to 15 cm (Barnes and Bowley 1974). Beyond this snow depth, however, changes in brightness do not normally occur. The snow line can be mapped to an accuracy of 20 km. A set of techniques for satellite snow mapping are covered in Barnes and Bowley (1974).

Three regions were isolated on the TIROS (Television Infrared Observation Satellite) ESSA (Environmental Sciences Services Administration) and Soviet Meteor-10 system satellite imagery. They included: 1) a snow depth of less than 2.5 cm, 2) snow depth from 2.5 to 10.2 cm, and 3) snow depth greater than 10.2 cm (Kurilova 1975, Kurilova et al. 1976). Snow depths greater than 10.2 cm were approximated only when climatic information on snow depth and weather conditions was available. The Meteor-10 satellite data are somewhat limited because of the low spatial resolution (1.25 km) of the photographs used in Kurilova's studies.

Percent snow-covered area maps of water basins in the southwestern U.S., the Sierra Nevada in California, the Pacific Northwest, and the northeastern U.S. are prepared weekly by NOAA/NESS (National Oceanic and Atmospheric Administration/National Environmental Satellite Service) starting on 1 November and ending when the snowpack is depleted (McGinnis et al. 1979). Since the 1977–78 winter season, operational coverage has been maintained for 30 basins, with the data supplied within 30 hr of a satellite overpass. The satellite images used for the snow mapping are from the VHRR (Very High Resolution Radiometer) sensor on the NOAA satellite and the VISSR (Visible and Infrared Spin-Scan Radiometer) on GOES (Geostationary Operational Environmental Satellite). The VHRR provides daily coverage over the U.S. in the visible wavelengths (0.6–0.7  $\mu\text{m}$ ) and twice-daily coverage in the thermal infrared wavelength (10.5–12.5  $\mu\text{m}$ ) band at a spatial resolution of 1 km for 256 energy levels. The VISSR imagery is available approximately every half hour over the United States at several resolutions in the visible and thermal infrared regions. The best resolution is 0.8 km for the visible band and 8 km for the thermal band. The 1-km

resolution available with the VHRR permits positioning of the snow limit to within 10 km (McGinnis 1975). Snow depth estimates have been found to correlate well with snow brightness for snow depth measurements less than 25 cm, although there is insufficient ground snow depth observations to conclude that satellite brightness values are a reliable indicator of snow depth (McGinnis 1975).

McGinnis (1975) examined a single NOAA-2 VHRR visible wavelength image over the southeast U.S. following a major snow storm. The satellite data was gridded into 32- $\times$ -32-pixel areas, corresponding to 1024 sq km on the ground. The greatest snow depth within each cell, as reported in the Department of Commerce climatological summaries, was paired with the highest brightness value. A power curve was found to describe the resulting plot. Small increases in depth caused brightness increases much larger than comparable increases at higher depths. McGinnis (1975) found that "once the snow accumulates to about 25 cm, most small plants are covered, only the larger shrubs and plants (corn stalks to trees) remain visible and in most cases will remain uncovered except in some mountainous areas where extremely heavy snows occur."

Matson and Wiesnet (1981) developed a monitoring program for the routine global mapping of snow cover using visible-channel imagery from the NOAA satellites. The interannual variability of regional snow cover can be described.

Lillesand et al. (1982) evaluated digital GOES visible data for four snow-covered days in Minnesota. Brightness values were compared against 13 rural nonforested sites located near National Weather Service snow depth measurement sites. Linear and second-order regression fits for the individual days resulted in variable  $R^2$  results. Similar analysis for forested sites was not reported. They did find that subtraction of non-snow brightness values for an October image from the snow image brightness values might have value in digitally determining the presence of snow in forested regions.

Imagery from the ESSA-9 camera system operating in the visible wavelengths was used to interpret snow conditions in the Quebec-Labrador region (Parry and Grey 1975). The imagery has a spatial resolution of approximately 5 km and a relative brightness scale of 64 levels. It was found that terrain factors, in particular the vegetation type, had a significant effect on the reflection values and, under similar snow conditions, physio-

graphic regions of the same type exhibit comparable brightness values.

A series of five-day composite minimum brightness (CMB) charts were used in the analysis. Reflection values were measured on a scale of 0–10% reflection when using a Densichron densitometer. A frequency–density analysis of the histograms of reflection values was used to see if regional snow conditions could be determined. “A distribution with high values and a moderate right skew represents a fresh snowfall over the greater part of the area, whereas a bimodal distribution indicates that the snowfall was restricted to particular parts of the region. With the same range of values and a left skew, the snow conditions can be interpreted as intermediate, which suggests settling, redistribution, ageing and compaction. A strongly unimodal, left-skew distribution indicates that the melt stage had been reached, and the subsequent shift of the modal class toward lower values reflects the progressive expansion of the snowfree areas” (Parry and Grey 1975).

There was a general consistency in the relative brightness of individual vegetation zones (in the range and the mean of each group) at all stages of the snow cover with the exception of the final melt period. The differences between the vegetation zones were particularly noticeable after periods of extensive snowfall.

The High Resolution Infrared Radiometer (HRIR) provides for 24-hr mapping of the Earth at an 8.5-km resolution. Nighttime infrared measurements of the Earth's surface and cloud top temperatures are provided in the 3.6- to 4.2- $\mu\text{m}$  wavelength range; during the daytime the HRIR measures reflected shortwave radiation in the 0.7- to 1.3- $\mu\text{m}$  range. The Image Dissector Camera System (IDCS) provides television coverage in the 0.5- to 0.7- $\mu\text{m}$  range at a 4.1-km resolution. Imagery from these two sensor systems was acquired over the Lake Winnipeg and the Sierra Nevada areas. It was found that “use of the near infrared data in combination with the visible imagery appears to permit the detection of thawing snow” (Strong et al. 1971). An explanation for the near-infrared brightness reversal was that “surface melting of the lake or snowpack caused the surface to absorb in the infrared while still reflecting in the visible” (Strong et al. 1971).

Melting snow could also be distinguished from snow that had not reached melting temperatures by using the visible and near-infrared bands of the Landsat MSS (Golding 1974). “Under clear skies, fresh or dry snow has a reflectivity of about 90%

in the visible part of the spectrum, and just slightly less in the near infrared. Such snow, therefore, appears light toned on both visible and near-infrared imagery. The surface of melting snow is covered by a thin film of water that absorbs most of the infrared radiation and therefore melting snow appears dark on the infrared imagery” (Golding 1974). However, ice is quite absorptive also. Old or refrozen snow would probably appear dark-toned in the near infrared region, too.

The Nimbus-7 satellite, launched on 24 October 1978, carries a multifrequency, dual-polarized microwave imager called the Scanning Multichannel Microwave Radiometer (SMMR). The goal of Kunzi et al. (1982) was “to show that the three snow-cover parameters: extent, snow water equivalent, and onset of snow melt can be determined using scanning multichannel microwave radiometer (SMMR) data... . Snow extent is determined for dry snow cover with depth  $\geq 5$  cm, snow water equivalent can be determined on a regional basis with  $\approx 2$  g/cm<sup>2</sup> rms accuracy, and the onset of snow melt is clearly visible by the detection of melt and refreeze cycles prior to snow runoff” (Kunzi et al. 1982). However, the main limitation of the satellite passive microwave data is the coarse spatial resolution, varying from 30 to 60 km depending on the frequency range (18–37 GHz). Kunzi et al. (1982) distinguished three classes of snow with the SMMR data, including 1) no snow, 2) dry snow, and 3) snow undergoing melt and refreeze cycles. Two algorithms were developed to determine snow depth and snow water equivalent to an accuracy of 6 cm for snow depth and 2 g/cm<sup>2</sup> for snow water equivalent based on the climatic regimes of Finland, southern Russia, and Canada (Kunzi et al. 1982).

“Microwave instruments, such as the SMMR, are the only remote sensors providing subsurface snow data. ...The SMMR is a very promising sensor for the detection of the onset of snow melt. This information is of great interest in snow hydrology and meteorology, it allows estimation of the time of runoff from a basin, and combined with the snow water equivalent information, allows prediction of the total water runoff” (Kunzi et al. 1982).

Landsat MSS (Multispectral Scanner Subsystem) band 5 (0.6–0.7  $\mu\text{m}$ ) has been the most useful for detecting and mapping mountain snow cover (Barnes and Bowley 1973). Changes in snowline elevation on two different dates ranging from 60 to 1220 m were mapped from the satellite imagery. The snow observed in MSS band 7 (0.8–1.1  $\mu\text{m}$ )

would normally be a high-elevation dry snow, whereas the dry and lower-elevation wet snow surfaces are seen in the MSS band 5 imagery (Barnes and Bowley 1974).

Barnes and Bowley (1974) discuss the problems of using satellite data to map snow. One problem is cloud cover obscuration for the visible and infrared systems. Passive and active microwave sensor systems may be a means to overcome this. Interpretation of the satellite data is another problem and includes distinguishing between snow and clouds, identifying snow in densely forested areas and in areas within mountain shadows, distinguishing between snow and highly reflective rock types, and mapping irregular, gatchy snowlines.

Landsat digital data for an alpine basin in Switzerland were classified, using a supervised parallel piped discriminant classifier, into three classes: 1) terrain totally covered by snow, 2) the transition zone—a mixture of melting snow patches and snowfree parts, and 3) snowfree terrain (Lichtenegger et al. 1981). In high mountainous areas, climatic changes with elevation play an important role in snowmelt. The alpine basin was separated into three elevation zones of 500 m intervals and then digitized. The areal extent of snow cover was calculated in terms of percentage for each elevation zone and used as input to a runoff model.

In another test site, located in the Upper Rhine, Lichtenegger et al. (1981) used the elevation data that was registered to a Landsat image to generate four additional channels that included an elevation zone, exposure angle, slope angle, and a lambertian brightness or reflectance map. During the classification process, the shadowed area could be detected and radiometric corrections with respect to the incident radiation angle could be carried out. It then becomes possible to extrapolate the snow coverage within a climatologically similar region when clouds are encountered on Landsat imagery.

A digital terrain model (DTM) was matched with two Landsat MSS scenes for a 1500-km<sup>2</sup> catchment area in eastern Switzerland (Seidel et al. 1983). A snow signature was developed from a scattergram of Landsat MSS band 5 versus 7 for mapping snow and snow-free areas. The DTM data were used to map the snow-cover distribution in percent with respect to slope and aspect for a given elevation zone. This provides a promising tool to extrapolate the snow cover from a cloud-free area to other parts of the subbasin that may be cloud-covered.

A quantitative measure of the water equivalent of the snowpack has not been obtained from Landsat photographic data products. Normally Landsat data has been used in a number of snowmelt runoff studies, principally to map the areal extent of snow for use in predicting snowmelt-derived streamflow (Anderson et al. 1974; Meier 1975c; Rango 1975, 1978, 1981; Rango et al. 1975; Thompson 1975; Rango and Itten 1976; Rango and Salomonson 1976; Shunying et al. 1980; Shafer et al. 1981; Dey et al. 1983). For example, Landsat satellite data have been used to monitor the disappearance of the snow cover throughout the melting period (Rango 1980a, b; Martinec and Rango 1981; Rango and Martinec 1981; Martinec 1982). Martinec (1975) developed a simple rainfall runoff model that incorporates the snowmelt runoff portion. The model takes into account the variability of the degree-day factor, discharge recession coefficients, and the areal extent of snow. The depletion curves relating the areal extent of snow cover to elapsed time were modified to relate snow coverage to accumulated temperature thawing degree-days. The total discharge volume from a drainage basin during the snowmelt season was simulated by using these depletion curves of the snow coverage (Rango and Martinec 1979; Rango 1980a,b, 1983). Rango and Martinec (1982) suggested that the depletion curves that normally relate the areal extent of the snow cover to elapsed time be modified to relate the snow coverage to the accumulated thawing degree-days to forecast runoff. It was then possible to estimate the total snow accumulation of the basin compared to previous years by observing the course of the modified depletion curve during the first few weeks of the snowmelt season. The water equivalent of the snow at the beginning of snowmelt was estimated, and an appropriate modified depletion curve was selected to use in the snowmelt runoff model (Rango and Martinec 1982, Rango 1983). Precipitation and air temperature are other input data required in the model. (The effect of solar radiation is automatically included in the degree-day factor in Martinec's model.) When the first satellite images are available for analysis, the results from the runoff model can be compared with the initial modified snow cover depletion curves. An updated, modified depletion curve can be prepared that will more closely match the actual mapped snow cover to be used in runoff forecasting. A more detailed description of the model can be found in Martinec et al. (1983).

The Applications Systems Verification and Transfer (ASVT) program for using operational applications of satellite snow-cover observations was conducted over four sites in the western United States from 1976 to 1978. Based upon the Colorado ASVT operational forecasting experience, a projected 6–10% relative improvement in forecasting occurred, with a benefit-to-cost ratio of 72:1, principally in the areas of hydroelectric energy and irrigation (Castruccio et al. 1981). Operational application of Landsat imagery was limited due to lack of data that was cloud-free and received in real time. The infrequency of Landsat coverage (every 18 days) magnified these problems.

Digital processing techniques have been used to map the areal extent of snow. Meier and Evans (1975) compared in a qualitative manner seven methods for estimating snow cover from Landsat imagery for several basins in Oregon and Washington. The seven methods were grouped into three categories: manual, interactive computer analysis, and digital pattern recognition techniques. The precision of the digital pattern recognition technique on a pixel-by-pixel analysis was found to be excellent, but at high cost and with slow to average speed. The analysis normally produces supplemental data. The technique is good for recognizing snow in trees or in shadow. The satellite images can be used to determine the mean altitude of the snow line or the percent of snow-covered area as a function of altitude (Meier 1975a). In addition, the calculated areal extent of snow has been found to be in good agreement with data on snow-covered areas from satellite images. Snow-covered area from Landsat images is obtained by radiance slicing (selecting the appropriate shade of gray to define the snow/no snow boundary), radiance-gradient slicing, time-lapse comparison (for instance, comparing portions of the same image in a snow-free and snow-covered condition, or successive snow-covered images), and by multispectral analysis (Meier and Evans 1975). The Landsat data offers additional advantages of high resolution, accurate map projection, and multispectral data allowing use of pattern recognition techniques (Meier 1974, 1975a).

Landsat data were found to be unsuitable for mapping the snowline in rolling forested terrain (Langham and Power 1977). Electronic density slicing techniques were performed on the satellite image. The resolution resulted in too great a sampling density in the transition regions since multiple minima were observed in the histograms.

Langham and Power would prefer to use areally averaged radiances at a resolution similar to NOAA satellites (1 km). However, a multispectral or pattern recognition analysis may be used to detect areas that combine the signatures of forest and snow cover (Meier and Evans 1975).

Single-band radiance thresholding of Landsat MSS band 5 data was the principal technique used in determining snow coverage for three Columbia River subbasins (Wiegman et al. 1975). The technique was supplemented by an editing procedure that involved reference to hand-generated elevation contours. A thematic map showing snow cover was documented by: 1) photography, 2) a numerical pixel count representative of the total area of snow in the scene and within the basin boundary, and 3) an array of single-digit numbers depicting tenths of snow cover for 2.5-km<sup>2</sup> grid cells within the basin.

The changes in the areal extent of snow cover measured on Landsat imagery have been found to correlate with changes in water equivalent recorded by a snow pillow (Anderson et al. 1974). As the water equivalent of snow increased, the areal extent of snow observed for the Caribou-Poker Creek watershed also increased. Another Landsat manual interpretation method used a coded snow cover classification scheme to account for vegetation cover, density, aspect, elevation, and slope to map the extent of snow (Katibah 1975a, b). Sequential aerial photography, Landsat imagery, and ground data on elevation, slope, aspect, and vegetation type were used to develop a subjective image interpretation key for a study conducted in the Feather River Watershed in Northern California (Draeger and Lauer 1974; Katibah 1975a, b; Sharp and Thomas 1975). A rapid and relatively simple manual interpretation technique was used to estimate acreages and extent of snow cover on satellite imagery by comparing no-snow Landsat images with corresponding snow-covered Landsat images.

Dallam and Foster (1975) used a snow-free Landsat scene to map the cover types and to serve as a reference base. Snow-covered Landsat scenes were then registered to the base image, so that any given point could be referenced to a cover type. Training sites were chosen visually to represent different snow cover classes. A supervised classification was used to produce a map of snow distribution versus cover type. Alföldi (1976) also used these basic concepts in a digital classification of a snow-covered Landsat scene. An enhancement of

the Landsat scene and subsequent classification was accomplished. A histogram analysis was used to make relative judgments about the snow cover. Alföldi (1976) suggested a simple technique for monitoring the presence of snow by developing a library of reference histograms with known snow characteristics and comparing an unknown histogram to estimate a best match. Prerequisites include identical areal coverage, cloud-free test and reference images, and no major changes in the land use/vegetative cover of the area. Alföldi (1976) indicated that total pixel brightness assumed a greater degree of importance for snow mapping when compared to the techniques of level slicing and band ratioing for digital image analysis of snow. He also indicated that snow cover mapping should be done on the basis of environmental factors affecting snowmelt rather than an arbitrary spatial grid. Ground visibility of snow through foliage and elevation were two suggested parameters.

Average snowpack characteristics, as well as the variability of these characteristics, were found to relate mainly to vegetation cover (FitzGibbon and Dunne 1979). In many small- to medium-size drainage basins in lowland areas, average snowpack characteristics are uniform and are a product of the regional climate (FitzGibbon and Dunne 1979). They found that variation of snow-cover properties was due to small-scale terrain interactions, which include local topography and vegetation, and the processes of snow-cover formation. FitzGibbon and Dunne demonstrated that snow-cover properties in a small, lowland subarctic drainage basin may be characterized according to vegetation cover as it controls snow redistribution through drifting. It is important that the extent and nature of the snow cover during the snowmelt be known, since the extent of snow cover partially determines the production of meltwater and reserves of water held in the pack (FitzGibbon and Dunne 1979).

Thomsen and Striffler (1980) classified the fractional snow-covered area of a Landsat pixel by detecting changes (differences in radiance) between a snowfree scene and snow-covered Landsat scenes. The water equivalent of the snow cover was inferred from the classified Landsat image, taking pixel elevation, aspect, and the image acquisition date into consideration. A watershed information system was developed to include a snowmelt run-off simulation that uses a spatial data format to drive snowmelt and lateral flow models for rout-

ing snowmelt through the soil profile to the nearest channel.

Anderson and Pagenhart (1957) did a multiple regression analysis and found that elevation, solar energy, and vegetation were important parameters influencing snow accumulation. An extensive review of the effects of elevation, aspect, and forest canopy on snow was accomplished by Meiman (1970). He concluded that differences resulting from canopy influences tend to be smaller than those associated with elevation changes. On the other hand, Anderson (1969) concluded that storm characteristics explain the longest variation in snow accumulation. Patch (1981) found that forest cover type may have the widest application in the utility of forest parameters in determining snow accumulation. He indicated that the forest cover could be of primary importance, as it can be and is altered by man, affecting spatial snowpack patterns and ultimately water yield and regime.

A snow mapping experiment comparing the identification of six snow-cover types was accomplished using three image processing systems—LARSYS Version 3, STANSORT-2, and General Electric IMAGE-100 (Itten 1975). In addition, other studies have focused on digital analyses of Landsat data in defining various snow-cover types (Bartolucci et al. 1975, Dallam and Foster 1975, Luther et al. 1975, Alföldi 1976). In these studies a quantitative estimate of water equivalent content associated with snow-cover types was not made. In one case it was suggested that spectral variations within the snowpack area could not be reliably determined because of detector saturation problems (Bartolucci et al. 1975).

Saturation of the MSS detector proved a problem for a study conducted over the American River Basin in California (McMillan and McGinnis 1975). A multiple regression equation was developed to predict the average snowpack density using the variables of MSS 7 radiance values, solar declination, sum of average daily air temperature above freezing since snowfall (thawing degree days), and snow course elevation. The results were not totally acceptable for immediate use in the Sierra Nevada. The average snowpack density was estimated from in situ albedo measurements obtained with two pyrhemometers (0.3–4.0  $\mu\text{m}$ ) for given site and storm data (McMillan and Smith 1975).

Another study used simulated infrared Landsat color composites and snow course data to estimate water equivalent related to the snowpack (Sharp



1975). Sampling units on the Landsat image were mapped to determine the areal extent of snow. An estimation of a snow water equivalent index was calculated using a linear regression equation relating the imagery to ground truth data.

Several researchers have reported techniques for estimating snow depth with aerial surveys. Steinhoff and Barnes (1976) used aerial remote sensing to determine by photogrammetric means the snow depth over a limited number of ground control targets. First, they photogrammetrically determined the ground surface elevation from aerial photography before snowfall. Using photography after a snow event, comparable ground elevations were determined. The difference between the two elevations would give an estimate of the snow depth. Multiple regression equations were developed for a given area relating snow depth to elevation, aspect, degree of slope, melt date, and vegetation density at various times during the melt season. Ideally, once a regression equation was developed for an area, the snow depth and water equivalent could be predicted by measuring the melt date and environmental variables. However, a uniform prediction of snow depth for an entire watershed from a single point measurement was not possible.

Blyth et al. (1974) discussed a similar technique using terrestrial-based stereopairs for determining depth differences for pre- and post-snow dates. They found the estimates of depth to be within 10% of the actual for 3-hectare study sites.

Warskow et al. (1975) conducted aerial surveys over a western hydrologic basin. They made visual estimates of snow depth, using the interactions of snow cover and the surrounding features of the landscape. It was estimated that dark rocks would be obscured by snow depths of 0–15 cm; grass stems would no longer be visible when the depth reached 15–20 cm; and half-shrubs were used as indices for the range 15–30 cm. Logs, fences, or markers were required for estimating snow depths greater than 30 cm. It was found that estimates were accurate within  $\pm 5$  cm, which was sufficient for their runoff volume forecasts.

Nicholson (1975) collected a temporal series of air photos to document the areal extent of snowpack duration throughout the melt season in a subarctic area of eastern Canada. Contours of duration, derived from the photographs, were related to maximum depth contours.

Ferguson and Lapczak (1977a,b) examined a portion of a NOAA-4 image over the Souris River

basin in Saskatchewan, Manitoba, and North Dakota. They compared brightness values to ground measurements of snow depth. A good correlation was found between the two variables. They caution, however, that the region is mostly flat, grass-covered terrain. The relationship between depth and brightness, they conclude, would not be evident for complex forested landscapes.

Mellor (1965) stated that remote sensing of the snow cover may have useful applications since the magnitude and wavelength of reflectance vary with snow types. The albedo for a layer of new snow can be quite high, approaching 91%; as the new snow grains coalesce and coarsen in texture the albedo falls steadily towards levels of 60 to 70% (Bergen 1975). In addition, the spectral reflectance declines from the combination of densification and increased particle size associated with aging (O'Brien and Munis 1975).

The albedo of a snow surface varies depending on the state of the surface. Fresh, undisturbed snow commonly reflects more than 70% of incoming solar radiation (Kondratyev 1969, Budyko 1974). A typical curve of reflectance as a function of wavelength shows a uniform high value greater than 0.8 at wavelengths between 0.35 and 0.90  $\mu\text{m}$  (Fig. 1). A marked drop in reflectance occurs in the near-infrared wavelengths, to a value less than 0.1, between 1.4 and 1.6  $\mu\text{m}$ . High reflectance was found in the visible portion with a sharp decrease in reflectance between 0.7 to 1.5  $\mu\text{m}$  (O'Brien and Munis 1975). This drop in near-infrared reflectance has been useful in discriminating snow surfaces from clouds in satellite imagery (Barnes and Smallwood 1975, Bartolucci et al. 1975).

Several aging processes decrease the reflectivity of a snow surface. Drifting, compaction, melt/freezing cycles, and micro-structure are so interrelated as to make it difficult to assess the precise role of each in changing reflectivity (O'Brien and Munis 1975). They also report that for a snowpack that had been naturally aged for about 40 hours, a ratio of about 0.8 spectral reflectance occurred for fresh to aged snow over the visible and near-infrared portions of the spectrum. This was for a specific case, so different natural aging conditions could result in different findings (H.W. O'Brien, pers. comm., 1984).

Using in situ measurements, McMillan and Smith (1975) found the square of albedo to be a good predictor of the average snowpack density. Bergen (1975) found that for snow grains greater than 1.5 mm in diameter, albedo variations are

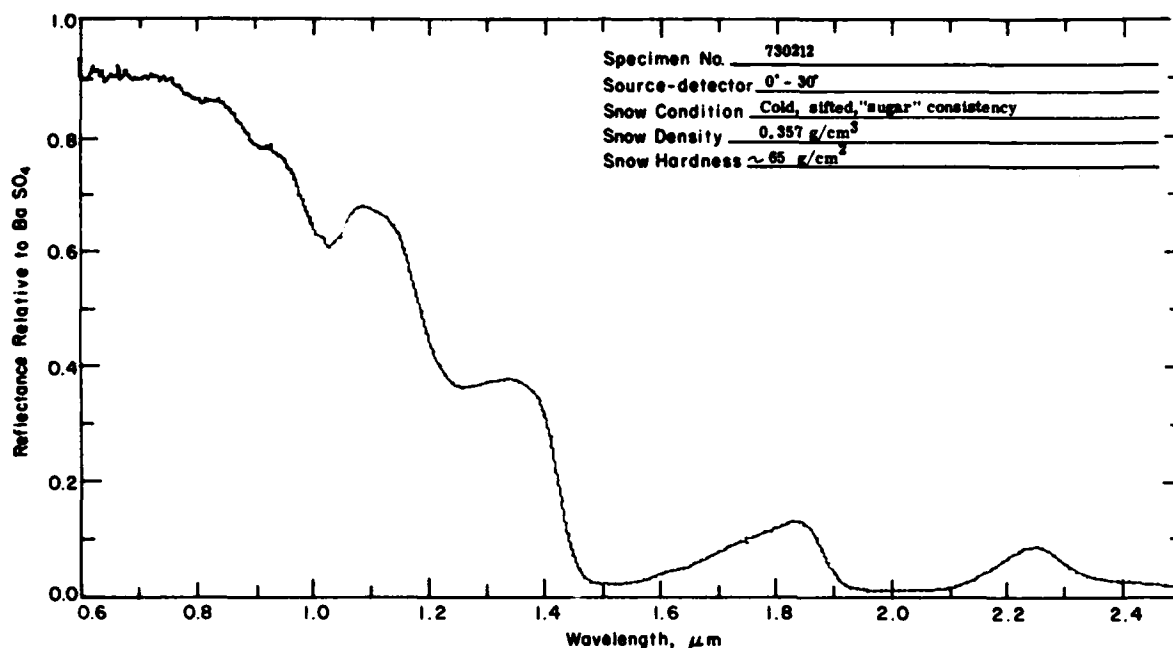


Figure 1. Typical spectral reflectance curve for snow (after O'Brien and Munis 1975).

primarily associated with density rather than grain size. In contrast, Bohren and Beschta (1979) reported no statistically significant change in albedo following artificial compaction by a snowmobile.

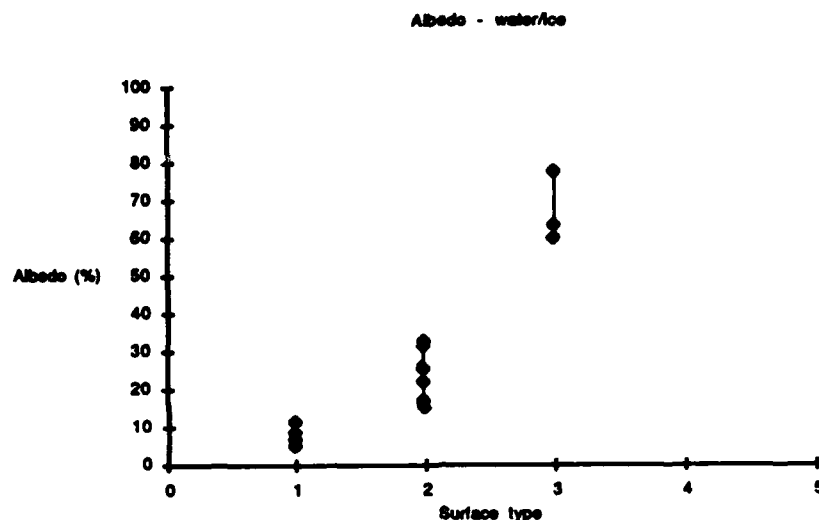
For shallow snow cover, the reflective properties of the underlying surfaces affect the surface albedo. Multiple reflections within the snow allow penetration of solar radiation to shallow depths. Giddings and La Chapelle (1961) show the extinction coefficient of snow to be a function of depth. With an underlying black surface, they showed albedo to increase rapidly with increasing depth, leveling off sharply as depth increased beyond 20 cm. O'Neill and Gray (1973) showed virtual independence of albedo from snow depth beyond depths of approximately 10 cm. Wiscombe and Warren (1980) indicated that the depth at which background influences occur depends on density and/or grain size.

These observations are based on measurements of surfaces composed of pure snow. It may be expected that the introduction of vegetation canopies would complicate the relationship of snow cover and albedo.

In natural landscapes, the reflectivity of an area during the winter will be determined by the unique properties of the surface components. "The regional albedo values during the winter months are dependent mainly on two factors, snow albedo

and the darkness of the nearly black bodies (i.e., trees and buildings, etc.)" (Kung et al. 1964). Thus, the structure of the vegetation canopy greatly influences the overall reflectivity. In their airplane measurements of surface beam albedo over Wisconsin, Kung et al. (1964) found agricultural lands under deep snow cover displayed albedos in the range of 50 to 70%. "When the ground snow cover is rather shallow, i.e., the snow depth is less than 5 in., the value of surface albedo is apparently related to the depth of snow and in turn probably to the area of patches covered by the snow, though further accumulation of snow does not seem obviously to increase the albedo" (Kung et al. 1964). Forested areas with deep snow reflected between 20 and 50% of the incoming solar radiation. Species composition of the forest accounted for considerable variability, for example, aspen and birch forests had albedos ranging from 38 to 50%; pine forests ranged from 19 to 37%; oak 32 to 42%; northern hardwood 19 to 36%; and swamp conifer 25 to 38%.

McFadden and Ragotzkie (1967) presented hemispheric albedo data for a variety of snow-covered regions observed with hemispheric solarimeters in flights over the boreal region of central Canada. Snow-covered tundra areas with frozen lakes had albedos in the range 70 to 92%, while forested lands with frozen lakes were in the range



Lake condition	Frozen		Partly frozen		No lakes	
Snow cover	Snow		No snow		Light snow	No snow

Figure 2. Albedo ranges for tundra and boreal forest regions (after McFadden and Ragotzkie 1967).

30 to 68% (Fig. 2). With lakes only partly frozen, snow-covered forests had albedos of 23 to 55%. It was found that the presence of frozen lakes raises regional albedos by a factor of at least 2 above that of forests without lakes. Additional albedo data for other regions are shown in Figure 3 for selected conditions ranging from water to ice- and snow-covered lakes. The more snow and ice cover on a lake, the higher the albedo.

The mechanics of obtaining hemispheric and beam albedo are different. "Beam albedo is calculated from the output of an upward-facing hemisphere radiometer and a radiometer with a downward-facing parabolic mirror that intercepts energy from a small area with a 4° beam width and focuses this energy on the radiometer. Hemispheric albedo, on the other hand, is determined from the records from the same type of upward-facing radiometer and down-facing solarimeter that has a full 2 $\pi$  steradian field of view. At an altitude of 500 ft the beam albedo system will instantaneously sample an area 35 ft in diameter, while the hemisphere system samples over the entire solid angle" (McFadden and Ragotzkie 1967). The values from the two different systems can be compared using a calibration factor of

$$(\text{beam albedo} \times 1.294) = \text{hemispheric albedo}$$

that was developed by Bauer and Dutton (1962), Dutton (1962), Kung et al. (1964), and McFadden and Ragotzkie (1967).

Leonard and Eschner (1968) conducted albedo measurements over a red pine plantation in northern New York State. On the morning following a snowfall of approximately 300 mm (30 mm water equivalent), an estimated 100 mm (10 mm water equivalent) had been retained by the forest canopy. At this time, mean albedo as measured by a tramway elevated solarimeter was about 18%. As the day progressed, a progressive decline in albedo was observed. Increasing temperature caused the dropping of clumps of snow, as well as some melt dripping. Most of the forest canopy was snow-free by 1300 hr. Albedo fell to approximately 15% and stayed fairly constant throughout the day. The reflectivity and canopy conditions during the afternoon were similar to measurements obtained immediately after a rainstorm. Leonard and Eschner suggest a value of 20% be used for albedo of snow-covered coniferous forest, although this may be conservatively high.

Using paired silicon cells above hardwood forests, Federer (1971) measured albedo at three northern sites in New York State and New Hampshire. Without snow, the canopy albedo was found to be about 10%. With ground snow cover,

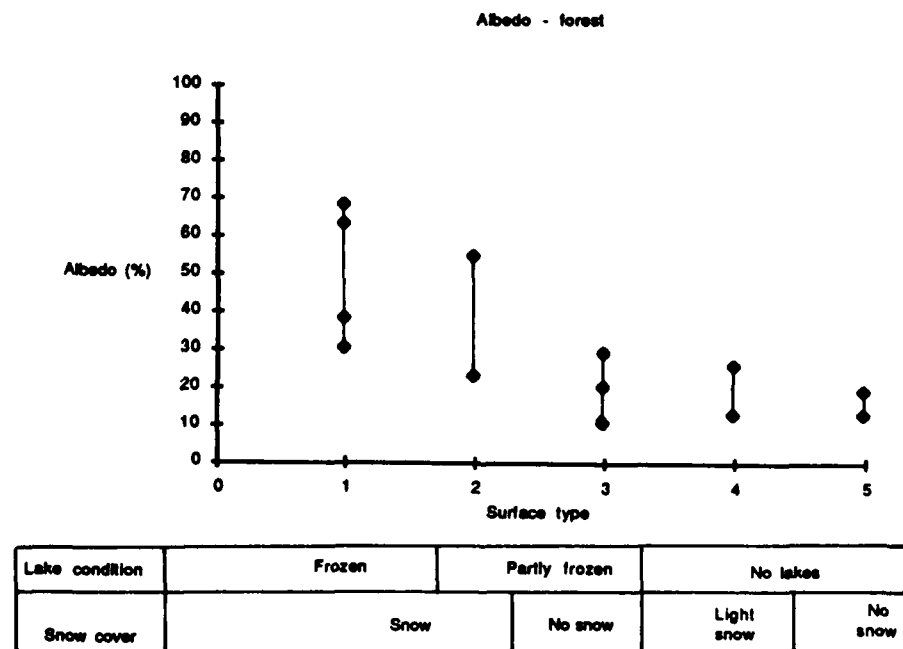
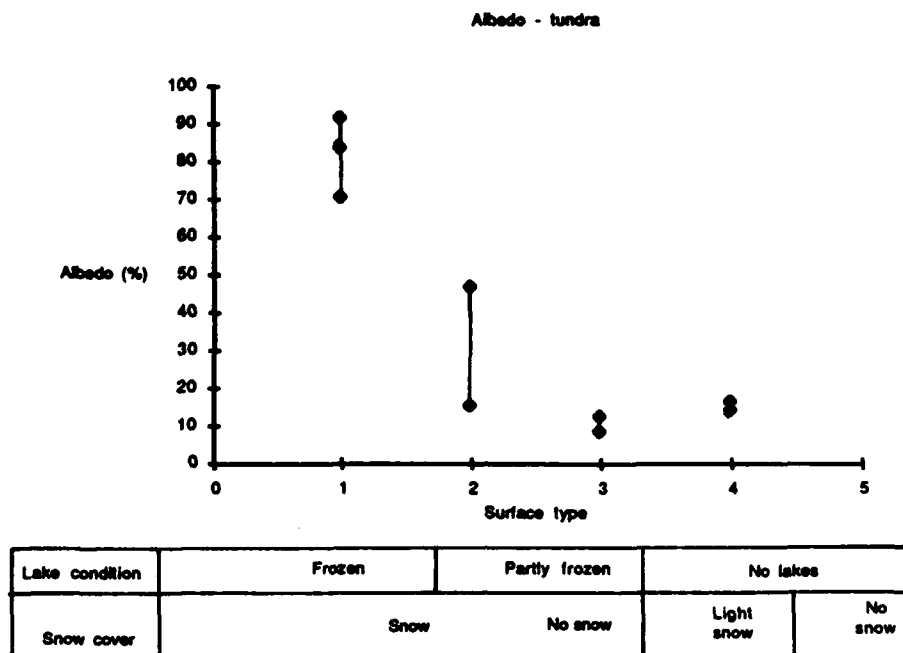


Figure 3. Typical albedos for selected conditions ranging from water to ice- and snow-covered lakes (data from McFadden and Ragotzkie 1967).

the albedo increased to values of 20% to 30% (Federer 1971).

Choudhury (1982) used Kung's aircraft albedo measurements (1964) to develop a model for the effective albedo of partially snow-covered areas. An equation for the fractional snow-covered area, dependent upon the snowpack thickness, was developed using Kung's data. These data were then compared to NOAA-2 VHRR data of McGinnis et al. (1975) for the southeastern United States. The predictions of the effective albedo model were in qualitative agreement with McGinnis's observations; for a given snow depth, the calculated brightness value was somewhat higher than the observed mean value (Choudhury 1982).

Spectral reflectance decreases with increasing particle size (Dunkle and Bevans 1956). Natural aging of the snow with normal settling and densification and the metamorphism of the snow cover or refreezing of partially melted snow on the surface and within the snowpack also cause a decrease in reflectance (Dirmhirn and Eaton 1975, O'Brien and Munis 1975). Hoarfrost formation on the surface could also raise the reflectance (H.W. O'Brien, pers. comm., 1984). The albedo measurement of the snow cover changes with the varying contribution of specular reflection from the snow surface with solar angle (Dirmhirn and Eaton 1975).

The reflectance of fine-grained snow is not greatly dependent on wavelength in the visible region, since surface reflectivity is high and single backscattering from the first layer of grains is apparently not very selective with respect to wavelength (Mellor 1965). However, as grain size increases, reflectance and surface reflectivity decrease. A relatively large proportion of the reflected light is backscattered from beneath the surface so that reflectance becomes inversely dependent on wavelength (Mellor 1965). The magnitude and wavelength dependence of reflectance will vary with snow type (Mellor 1965). The reflectance of snow is determined by the illumination conditions, by the surface characteristics, and by the subsurface backscattering (Mellor 1977).

Warren (1982) reviewed the optical properties of snow in the solar ( $0.3 \leq \lambda \leq 5 \mu\text{m}$ ) and thermal infrared ( $5 \leq \lambda \leq 40 \mu\text{m}$ ) wavelength regions, which are important for determining the climatic role of snow and for affecting snowmelt. He states that the bidirectional reflectance distribution function, which is unevenly distributed among the

reflection angles, must be known to interpret individual satellite measurements. The function has been measured at the snow surface and at the top of the atmosphere, but its dependence on wavelength, snow grain size, and surface roughness is unknown (Warren 1982). Warren recommends that angular detailed measurements of the bidirectional reflectance for various wavelengths, grain sizes, and surface conditions should be given a high priority for remote sensing applications.

"Dozier et al. (1981) have used a model of Wiscombe and Warren (1980) to calculate snow albedos integrated over channels 1 and 2 ( $0.5\text{--}0.7 \mu\text{m}$  and  $0.7\text{--}1.0 \mu\text{m}$ , respectively) of the NOAA TIROS-N satellite. The hope is to deduce grain size from a near-infrared channel, where depth and contaminants have no effect on albedo, and then use the deduced grain size together with the channel 1 data to infer snow water equivalent depth below some threshold value around 100 mm. Among the difficulties in this approach are (1) the conversion of bidirectional reflectance to albedo, (2) the poor location of channel 2 for this purpose (an ideal channel would be located in the region  $1.0\text{--}1.2 \mu\text{m}$ , where the sensitivity of albedo to grain size is greatest), and (3) the fact that visible albedo reduction can be due to impurities as well as to thinning of the snowpack. Dozier et al. (1981) were apparently able to detect the thinning of the snowpack at the end of the melting season on some Canadian lakes" (Warren 1982).

Other research indicates that the  $1.25\text{--}1.35\text{-}\mu\text{m}$  spectral region would be an even better choice due to the sensitivity of albedo to grain size (H.W. O'Brien, pers. comm., 1984).

O'Brien and Koh (1981) observed the change in spectral reflectance with a few narrow-band filters as a thick snow cover decayed. They documented in a qualitative manner the transition of the spectral reflectance of snow to the spectral reflectance of grass.

Several investigators reported that snow accumulation is unique for specific vegetative and landscape units (Steppuhn and Dyck 1974, Adams 1976, Steppuhn 1976, Adams and Barr 1979, Fitz-Gibbon and Dunne 1979, Mathers 1980, Adams and Roulet 1981). As discussed earlier, when considering an open, undisturbed snowpack, snow depths greater than about 13 cm will not display greater reflectivity with increasing accumulation. However, when the snow is found intermixed with a vegetation canopy, the interactions are more complex. It could be hypothesized that as the bright snow increases in depth, the darker extent

of the plant cover (both horizontal and vertical) becomes obscured. The reflectance might increase, ideally, until the uppermost crown of the vegetation is completely overlain by about 13 to 25 cm of snow (McGinnis et al. 1975).

Snow cover in different roughness zones shows systematic differences in snow water equivalent, average density, and depth (Granberg 1975). Average water equivalent was found to be largely independent of roughness zone, except for boundary zones (Granberg 1975). Surface roughness comprised topographic and vegetation roughness. The height-to-width ratio of topographic roughness is considerably less than unity, and vegetation roughness has a height-to-width ratio considerably greater than unity. The effect of roughness changes through winter has shown that snow accumulation results in a progressive reduction in surface roughness (Granberg 1972). Six roughness zones were selected in Granberg's study and included closed woodland, open woodland, regenerating burn, recent burn, bog, and lake.

Warren (1982) and NASA (1982) listed the snow parameters affecting the visible, near-infrared, thermal infrared, and microwave wavelength regions (Table 1). "To detect individual snow parameters unambiguously from satellite, one must therefore examine the snow at several wavelengths simultaneously. For remote sensing applications, angularly detailed measurements of the bidirectional reflectance for various wavelengths, grain sizes, and surface conditions should be given high priority" (Warren 1982).

### The Landsat CCTs

The Landsat satellites (Landsat-1 through -4) circle the earth in a 920-km, near-polar orbit once every 103 minutes, each completing approximately 14 orbits per day. The multispectral scanner (MSS) on each satellite is a line-scanning device that uses an oscillating mirror to continuously scan perpendicular to the spacecraft (USGS and NASA 1979). Six lines are scanned simultaneously in each of four spectral bands for each mirror sweep, and radiation is sensed simultaneously by an array of six detectors in each of four spectral bands from 0.5 to 1.1  $\mu\text{m}$  (USGS and NASA 1979). During image data processing, a black and white photographic data product can be produced of an area approximately 185 km on a side for the following spectral regions: MSS band 4 (0.5–0.6  $\mu\text{m}$ ), MSS band 5 (0.6–0.7  $\mu\text{m}$ ), MSS band 6 (0.7–0.8  $\mu\text{m}$ ) and MSS band 7 (0.8–1.1  $\mu\text{m}$ ). This information is also available in digital form on a CCT. Landsat data products can be obtained from the EROS Data Center, Sioux Falls, South Dakota.

The standard Landsat CCT was computer-processed to produce a geometrically corrected tape with the pixels transformed to a UTM (Universal Transverse Mercator) projection. This geometrically corrected CCT comprises 2432 scan lines, with each scan line covering 3200 pixels. Each pixel represents an area on the ground having dimensions of 61  $\times$  76 m. Differing levels of radiant energy for each pixel within the scene are registered on a scale from 0 to 127 (minimum [black] to maximum [white]) for bands 4, 5, and 6 and 0 to 63 for band 7 (Thomas 1975).

**Table 1. Parameters affecting albedo and emissivity of snow (after Warren 1982 and NASA 1982).**

<i>Snow property</i>	<i>Visible solar albedo</i>	<i>Thermal infrared emissivity</i>	<i>Microwave emissivity</i>
Grain (or crystal) size	Yes*	Yes	Yes
Zenith (or nadir) angle	Yes*	Yes	Yes
Snow depth	Yes†		Yes
Contaminants	Yes		
Liquid water content	Yes	Yes	Yes
Surface roughness	Yes		Yes
Density			Yes
Temperature		Yes	Yes
Stratification			Yes
Soil state, moisture, roughness, vegetation			Yes

\* If snowpack is thin or impurities are present.

† Shallow, up to a few centimeters.

Figure 4 shows the Landsat orbital tracks over northern New England. The ideal path and rows for Landsat coverage over the Upper Saint John River Basin were path 13, rows 27 and 28. However, side lap does occur with the adjacent paths of 12 and 14. Table 2 shows the available Landsat coverage over the Upper Saint John River Basin for the 1977-78, 1978-79, and 1979-80 winter seasons.

#### The computer algorithm

The geometric correction of the digital data and the computer classification algorithms used in the analyses were developed at the NASA Goddard Institute for Space Studies (GISS) (Ungar 1977). The geometric correction provides for a 1:24,000 scale computer print-out, which enables one to lo-

cate test sites more accurately. The classification algorithms used were part of the GISS-MAP1 (Multispectral Image Analysis Package) program. In this package, digital count values for the four Landsat MSS bands are converted to radiances (measured in  $\text{mW cm}^{-2}/\text{sr}$ ) using calibration-derived gains and offsets. The MAP1 algorithm developed for analysis of the digital data allows for both components of the data—one of the four wavelength bands and the associated radiance value for each pixel—to be evaluated when classifying the Landsat data in various categories. Color differences consider the direction of the pixel vectors relative to the four-band axes. Brightness differences are based on the summation of the four bands.

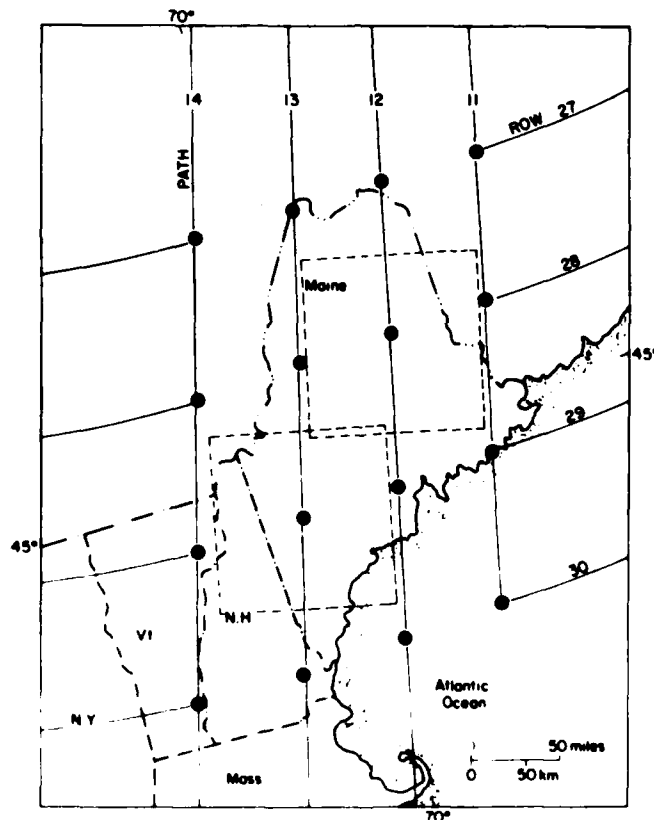


Figure 4. Landsat orbital tracks over the northern Maine area. Image centers are indicated by the solid circles; the dashed outlines show ground coverage per frame and image overlap and sidelap.

**Table 2. Landsat satellite overpasses for the Upper Saint John River Basin.**

**a. 1977-78 winter season.**

<i>Date</i>	<i>NASA scene ID</i>	<i>Path/row</i>	<i>Cloud (%)</i>
1 Dec 77	6044-14125	12/27	90
1 Dec 77	6044-14132	12/28	90
3 Dec 77	6046-14243	14/27	80
19 Dec 77	6062-14122*	12/27	70
19 Dec 77	6062-14125*	12/28	90
20 Dec 77	6063-14180*	13/27	20
20 Dec 77	6063-14183*	13/28	80
21 Dec 77	6064-14235*	14/27	80
21 Dec 77	6064-14241*	14/28	90
6 Jan 78	21080-14121*	12/27	10
6 Jan 78	21080-14124*	12/28	10
7 Jan 78	21081-14128*	13/28	60
8 Jan 78	21082-14234*	14/27	80
8 Jan 78	21082-14241*	14/28	90
24 Jan 77	21098-14123	12/27	80
24 Jan 77	21098-14130	12/28	60
25 Jan 77	21099-14182	13/27	90
25 Jan 77	21099-14184	13/28	90
26 Jan 77	21100-14243	14/28	90
11 Feb 77	21116-14133*	12/27	10
11 Feb 77	21116-14140*	12/28	20
12 Feb 77	21117-14192*	13/27	70
12 Feb 77	21117-14195*	13/28	70
13 Feb 77	21117-14251*	14/27	30
13 Feb 77	21118-14253*	14/28	30
1 Mar 78	21134-14144*	12/27	30
1 Mar 78	21134-14150*	12/28	0
2 Mar 78	21135-14203*	13/27	30
2 Mar 78	21135-14205*	13/28	10
3 Mar 78	21136-14264	14/28	50
9 Mar 78	30004-14421	12/27	10
9 Mar 78	30004-14423	12/28	10
28 Mar 78	30023-14414	12/27	90
28 Mar 78	30023-14420	12/28	90
29 Mar 78	30024-14472	13/27	80
29 Mar 78	30024-14475	13/28	80
30 Mar 78	30025-14533	14/28	90
15 Apr 78	30041-14415	12/27	90
15 Apr 78	30041-14422	12/28	80
17 Apr 78	30043-14534	14/28	70
25 Apr 78	21189-14235*	13/28	90
26 Apr 78	21190-14294*	14/28	10

**b. 1978-79 winter season.**

<i>Date</i>	<i>NASA scene ID</i>	<i>Path/row</i>	<i>Cloud (%)</i>
5 Dec 78	30275-14433	12/27	90
5 Dec 78	30275-14440	12/28	80
6 Dec 78	30276-14491	13/27	40
6 Dec 78	30276-14494	13/28	70
7 Dec 78	30277-14552	14/28	40
23 Dec 78	30293-14432	12/27	80
23 Dec 78	30293-14435	12/28	80
24 Dec 78	30294-14491*	13/27	10
24 Dec 78	30294-14493*	13/28	0
25 Dec 78	30295-14552	14/28	90
10 Jan 79	30311-14433	12/27	10
10 Jan 79	30311-14435	12/28	10
11 Jan 79	30312-14491*	13/27	10
11 Jan 79	30312-14494*	13/28	0
12 Jan 79	30313-14552	14/28	10
19 Jan 79	21458-14295	12/27	0
19 Jan 79	21458-14301	12/28	0
28 Jan 79	30329-14433	12/27	90
28 Jan 79	30329-14435	12/28	90
29 Jan 79	30330-14491	13/27	90
29 Jan 79	30330-14494	13/28	90
15 Feb 79	30347-14432	12/27	10
15 Feb 79	30347-14435	12/28	0
16 Feb 79	30348-14491	13/27	80
16 Feb 79	30348-14493	13/28	60
17 Feb 79	30349-14551	14/28	10
17 Feb 79	30349-14545*	14/29	
5 Mar 79	30365-14431	12/27	90
5 Mar 79	30365-14434	12/28	90
6 Mar 79	30366-14485	13/27	90
7 Mar 79	30367-14550	14/28	90
23 Mar 79	30383-14430	12/27	30
23 Mar 79	30383-14432	12/28	10
29 Apr 79	30420-14485	13/27	90
29 Apr 79	30420-14492	13/28	90

\* Landsat CCTs available at CRREL.



Table 2 (cont'd).

c. 1979-80 winter season.

Date	NASA scene ID	Path/row	Cloud (%)
1 Dec 79	30636-14454	13/27	90
1 Dec 79	30636-14460	13/28	70
2 Dec 79	30637-14514	14/28	90
18 Dec 79	30653-14393	12/27	20
18 Dec 79	30653-14395	12/28	10
19 Dec 79	30654-14451*	13/27	10
19 Dec 79	30654-14453*	13/28	10
20 Dec 79	30655-14512	14/28	10
5 Jan 80	30671-14385	12/27	10
5 Jan 80	30671-14391	12/28	50
6 Jan 80	30672-14443*	13/27	0
6 Jan 80	30672-14450*	13/28	10
23 Jan 80	30689-14385	12/27	90
23 Jan 80	30689-14392	12/28	90
24 Jan 80	30690-14444	13/27	80
24 Jan 80	30690-14450	13/28	70
10 Feb 80	30707-14383	12/27	10
10 Feb 80	30707-14390	12/28	10
11 Feb 80	30708-14441*	13/27	0
11 Feb 80	30708-14444	13/28	40
12 Feb 80	30709-14502	14/28	90
29 Feb 80	30726-14434	13/27	40
29 Feb 80	30726-14440	13/28	90
17 Mar 80	30743-14372	12/27	70
17 Mar 80	30743-14374	12/28	70
18 Mar 80	30744-14430	13/27	90
18 Mar 80	30744-14433	13/28	90
19 Mar 80	30745-14491	14/28	20
4 Apr 80	30761-14364	12/27	70
4 Apr 80	30761-14370	12/28	90
5 Apr 80	30762-14422	13/27	90
5 Apr 80	30762-14424	13/28	90
23 Apr 80	30780-14414	13/27	90
23 Apr 80	30780-14420	13/28	90
24 Apr 80	30781-14475	14/28	90

\* Landsat CCTs available at CRREL.

The Landsat MSS observation (pixel) may be thought of as a point in a four-dimensional "color" space, where the values along each axis represent the radiant energy received by the satellite in one of the four bands (Fig. 5a). Observations that lie in a similar direction from the origin in this four-dimensional color space are said to be similar in color regardless of their total radiant energy.

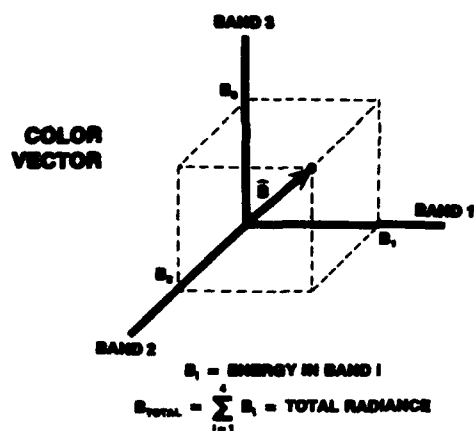
The distance (length) of an observation from the origin is a measure of the total radiance associated with that point. The algorithm is primarily designed to combine observations that are similar in color into the same classification category. There is provision for evaluating brightness differences between pixels and for weighting these differences in with the color discriminant when constructing the classification categories.

Discrimination based solely on color is obtained when the difference in direction between the solar vectors (observations) is examined. If the angle between the observations is smaller than some user-defined criterion, the vectors are considered to be lying in the same direction and, therefore, the observations are placed in the same category.

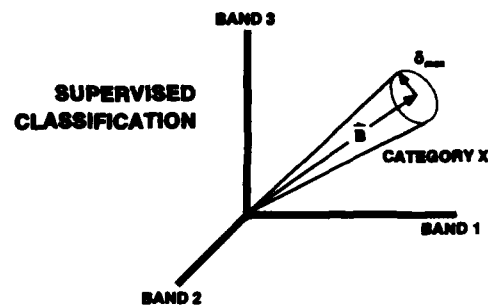
In addition to discrimination based solely on color, the GLSS algorithm provides the capability of weighting total radiance differences into the discriminant equation for classification. The percent difference in brightness between two observations is computed. The calculated normalized difference is then combined with the color difference angle (expressed in steradians) by performing a weighted average in the RMS (root mean square) sense. This brightness-weighted quantity is now compared with the user-defined criterion ( $\delta_{\max}$ ). Thus, in the classification process, a relatively small weighting of brightness allows very large brightness differences to disqualify observations that are similar in color from membership in the same category, thereby adding a second level of discrimination.

There are two modes in which this classification scheme may be used: supervised and unsupervised. In the supervised mode the user specifies a signature, here shown as  $\hat{B}$ , the energy distribution in the four Landsat bands. If an observation lies within a solid angle smaller than the user-defined criterion,  $\delta_{\max}$ , it is said to belong to the category represented by the multispectral signature,  $\hat{B}$  (Fig. 5b). Therefore, all vectors lying within a cone of angle  $\delta_{\max}$  about signature  $\hat{B}$ , which represents category  $X$ , belong to category  $X$ .

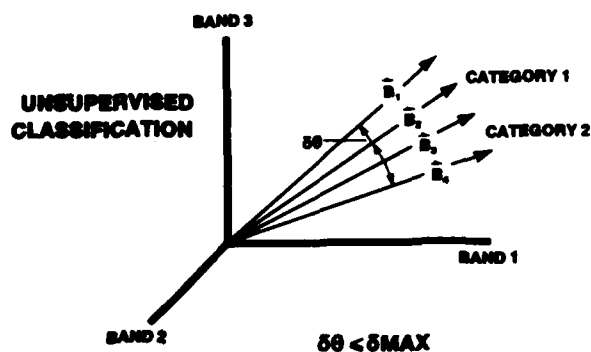
In the unsupervised classification a maximum value of  $\delta_{\max}$  is specified by the user for the combined color-brightness difference. If the color-brightness difference is less than or equal to  $\delta_{\max}$ , then pixels  $i$  and  $j$  are grouped into the same category.



a. A color vector illustrated for three-dimensional space, but all four Landsat bands are used in the classification process.



b. Supervised mode. The user-defined criterion,  $\delta_{max}$ , defines category X about the signature B. Any color vector that lies within this cone belongs to category X. This is illustrated for three bands; however, all four Landsat bands are used in the computer classification algorithm.



c. Unsupervised mode.  $\hat{B}_1$  is similar in direction to  $\hat{B}_2$  ( $\delta\phi \leq \delta_{max}$ ) and is placed in category 1.  $\hat{B}_3$  is similar in direction to  $\hat{B}_2$  and is placed in category 2. However,  $\hat{B}_3$  is also similar in direction to  $\hat{B}_1$  (category 1), so category 1 is merged with category 2.

Figure 5. The concept of the four-dimensional "color" space used in the computer classification algorithm (after Merry et al. 1977).

To illustrate this in terms of equations used in the computer analysis, each pixel's signature is represented by a real vector in the four-dimensional space. The signature is the sum of the four components and is defined as the real vector represented by the following equation:

$$\hat{S} = (S_1, S_2, S_3, S_4). \quad (1)$$

The unit vector is used to define the direction of the pixel. The magnitude of  $S$  is defined as the square root of the sum of the squares of the four components:

$$|S| = \sqrt{S_1^2 + S_2^2 + S_3^2 + S_4^2} \quad (2)$$

The unit vector is then defined as:

$$S = \frac{\hat{S}}{|\hat{S}|} \quad (3)$$

Note that the magnitude of unit vector  $S$  will always equal 1. The unit vector and real vector are calculated for each pixel.

Each pixel  $i$  and  $j$  is compared with every other pixel in terms of color difference and brightness difference. The color difference is the absolute value of the difference in the unit vectors:

$$\delta_c = |S_i - S_j|. \quad (4)$$

The brightness difference is the sum of the total radiance or brightness divided by two. This number is divided into the absolute value of the difference in the total radiances between two pixels:

$$\delta_b = \frac{|B_i - B_j|}{(B_i + B_j)/2} \quad (5)$$

The differences in color and brightness between pixels  $i$  and  $j$  are then combined to calculate an overall signature difference between the two pixels.  $W$  is a parameter for specifying the relative weighting given to the color and brightness differences. The overall signature difference is defined as:

$$\Delta_{ij} = \sqrt{W\delta_c^2 + (1-W)\delta_b^2} \quad (6)$$

If one suspects that the ground categories display greater brightness differences than color differences, one may wish to increase the importance of brightness differences when using the  $W$  parameter to better differentiate among the ground categories. If  $W$  equals 0, then only the brightness difference is used. If  $W$  is set to 1, then the color difference is used for the signature difference between two pixels.

In the unsupervised mode the color vector corresponding to the first observation is compared to all subsequent observations. If color vector 1 is similar in direction to color vector 2 (i.e.  $\delta\theta \leq \delta_{\max}$ ), observation 2 is placed in the same category as the first observation (Fig. 5c). In a similar fashion, observations subsequent to observation 2 are compared to the second observation and so on, right up to the last observation. If in the process of constructing categories a member is found that belongs to a previous category, the new category is chained (or linked) to the original classification category, forming one joint category (Ungar

1977). In effect the unsupervised classification will form several categories based on a criterion specifying maximum color difference permissible between members of the same category:

$$\Delta_{ij} \leq \delta_{\max} \quad \text{or} \quad \delta\theta \leq \delta_{\max} \quad (7)$$

As shown,  $\hat{B}_i$  is similar in direction to  $\hat{B}_j$  (cone of angle  $\delta\theta \leq \delta_{\max}$ ) and is placed in category 1 (Fig. 3).  $\hat{B}_i$  is similar in direction to  $\hat{B}_j$  and is placed in category 2.  $\hat{B}_i$  is also similar in direction to vector  $\hat{B}_j$  (category 1). Therefore, category 1 is merged with category 2.

When the pixels are chained together in clusters, a cluster represents a category defined by two extreme signatures. This hypothesis is due to the fact that pixels within certain ground cover classes display a continuous variation in signature over space between the two extreme signatures, for example, mixtures of vegetation and urban areas. The computer program searches for the pixel in a category for which the color-brightness difference is largest, say  $\hat{S}_i$ , and this pixel is called the first pure type. Next the program determines the second pixel in that category that is furthest in terms of signature from the first pure-type pixel. This pixel is then the second pure type, say  $\hat{S}_j$ .

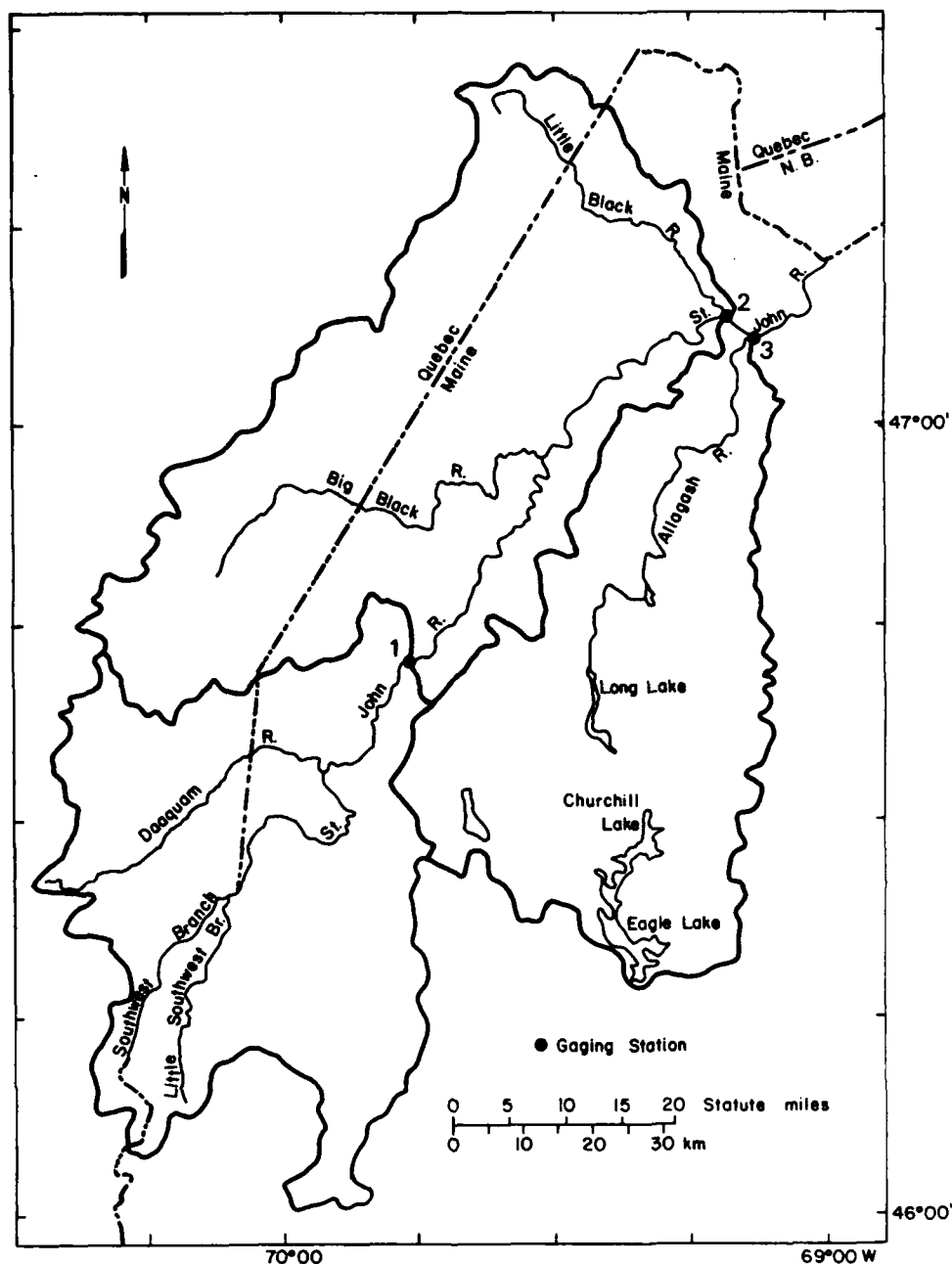
Once these two pure-type pixels are found, then each pixel in that category can be expressed as a linear combination of the two pure types. Therefore, the vector signature for an observed pixel,  $\hat{S}$ , is defined by the following equation, with  $\hat{S}_i$  and  $\hat{S}_j$  representing the two pure types (a two-component mixture) with  $\eta$  to define the fraction between the two extremes:

$$\hat{S}_{\text{obs}} = \eta\hat{S}_i + (1-\eta)\hat{S}_j. \quad (8)$$

The digital processing of the Landsat CCTs was accomplished through a cooperative agreement with NASA GISS. Computer algorithms for the analysis of the digital data were developed at GISS (Ungar 1977). These algorithms were accessed using the CRREL remote entry terminal to the main computer facility (IBM 4341), located at GISS in New York City.

#### Physical setting

The Upper Saint John River Basin was selected because the SSARR model is used for operational flood forecasting by the New Brunswick Flood Forecast Centre. The subbasins evaluated included the Allagash (3240 km<sup>2</sup>), Dickey (7410 km<sup>2</sup>), and Ninemile Bridge (3340 km<sup>2</sup>) (Fig. 6).



**Figure 6. Location of the outflow points for the Ninemile Bridge (1), Dickey (2) and Allagash (3) subbasins of the Upper Saint John River Basin.**

The climate of this region is humid continental. The average annual precipitation is approximately 91 cm and occurs uniformly throughout the year, with about 30% in the form of snow. Average snow depth ranges between 51 and 102 cm, with the upper limit exceeding 127 cm (New England Division, Corps of Engineers 1967). Water equivalent of the snowpack reaches a maximum in late March and usually exceeds 25 cm.

The geology and vegetation of the area were previously mapped and served as a data base of site characteristics in this study (McKim 1975, McKim and Merry 1975, Environmental Research and Technology, Inc. 1977). Elevations within the subbasin range from 150 to 600 m, and forest cover varies from 76 to 93%.

The snowpack in the Saint John River Basin is of shallow to medium depths of less than 30 cm of

water equivalent for an overall accumulation (Hansen 1975). There are rare maximum accumulations of 32 cm of water equivalent. The snow-pack melts and contributes to runoff in a time period of less than 5 weeks. Coincident rainfall at the time of snowmelt normally occurs during the spring runoff. Ice movement also complicates the runoff process.

Most (85%) of the watershed is covered by a dense forest with predominantly coniferous forests in the valleys and lower slopes. Hardwood forests cover the hilltops of minor relief. Mixed forests occur principally along the valley sides. Forestry operations create new areas of clearcuts. The region of study lies in the physiographic province of the Chaleur Upland. The mean elevation of the upland province is 250 to 300 m.

### The SSARR model

The SSARR model was developed for use in the North Pacific Division of the U.S. Army Corps of Engineers (U.S. Army Engineer Division, North Pacific 1975). The model is used for operational river forecasting and river management activities in connection with the Cooperative Columbia River Forecasting Unit, sponsored by the National Weather Service, U.S. Army Corps of Engineers, and the Bonneville Power Administration. The SSARR model was previously calibrated for the Saint John River Basin by the New Brunswick

Flood Forecast Centre, Canada, to forecast runoff due to snowmelt and precipitation (Power et al. 1980).

The SSARR model is a continuous deterministic simulation model of the river basin system (Fig. 7). Streamflow is synthesized by evaluating snowmelt and rainfall. There are three basic components in the SSARR model:

- 1) A generalized watershed model for synthesizing runoff from snowmelt, rainfall, or a combination of the two.
- 2) A river system model for routing streamflows from upstream to downstream points through channel and lake storage.
- 3) A reservoir regulation model in which reservoir outflow and contents may be analyzed along with synthesized inflow and free flow or any of several modes of operation (U.S. Army Engineer Division, North Pacific 1975).

In this study only the generalized watershed portion of SSARR was used to predict outflow from the three gauging stations (Fig. 6).

Snowmelt is calculated in the SSARR model by use of the temperature index method or a generalized snowmelt equation with additional options of subroutines for a snow-cover depletion approach or the elevation band approach. Because meteorological data were available from a station near the Allagash gauging station, the temperature index

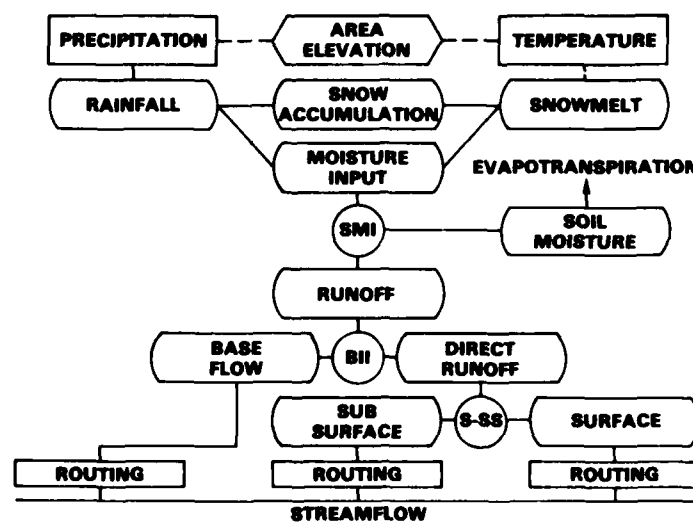


Figure 7. Schematic of the SSARR (Streamflow Synthesis and Reservoir Regulation) model (after U.S. Army Engineer Division, North Pacific 1975).

method was selected. Precipitation and air temperature values were used from this site. The watershed elevation distribution versus percent area data were input as a table to the SSARR model. This table is used to relate freezing level elevations to percentage of snow-covered area and is required only for the snowmelt computations. The elevation band subroutine was selected so that the snow water equivalent data could be used as input. An inventory of snow water equivalent is then maintained on each elevation band.

Flood forecasting models have been developed for the Saint John River Basin. The New Brunswick Electric Power Commission and the New Brunswick Department of the Environment have cooperated to adapt the SSARR program to the Saint John River Basin (Smith 1980, Hansen 1975). Ground truth maps of the snow survey data have been combined with the satellite image interpretation of the snow-covered area for input to the SSARR model.

Snow cover was first mapped in the Saint John River Basin by the Earth Satellite Corporation for the 1974 melt period. Numerical estimates of snow-covered area were accomplished for nine zones using NOAA visible band imagery (Hansen 1975). In 1975 NOAA/NESS supplied snow-covered area estimates as backup to the River Forecast Center. Landsat image interpretation was also accomplished in 1975 in conjunction with low-level infrared photography obtained over 10 snow survey locations (Ferguson and Lapczak 1977a,b). Snow-cover measurements have since been coordinated with overflights of the Landsat satellite.

## APPROACH

In northeastern North America snow accumulation has been found to be specific for vegetative and landscape units (Steppuhn and Dyck 1974, Adams 1976, Adams and Barr 1979, FitzGibbon and Dunne 1979, Adams and Roulet 1982). Because of this phenomenon, 11 snow courses were established based on vegetative type, slope, aspect, and elevation (Table 5, Fig. 8). The sites were selected primarily on the basis of four vegetation classes: mixed, hardwoods, softwoods, and cleared land. When possible, various elevations (from 180 to 450 m) and aspects (north, south, east, and west) within an 8-km radius of Allagash were selected for each vegetation type.

A meteorological station was installed at Allagash, Maine, to obtain background data on local climatic conditions. The instrumentation included a rain gauge, maximum and minimum thermometers, a hygrothermograph, and an anemometer. In addition, a Landsat data collection platform was installed at site 13 to measure air and ground temperatures and wind passage during the 1978-79 winter season.

Measurements of snow depth and water equivalent were obtained at the 11 snow courses in conjunction with the Landsat-2 and -3 imagery for the 1977-78, 1978-79, and 1979-80 winter seasons. Snow pit studies were conducted at three of the 11 sites (sites 1, 9, and 13) during each Landsat pass to characterize snow properties. Weekly snow course and snow pit measurements were performed at the meteorological station (site 1).

Table 3. Snow course site characteristics in the Allagash area, Maine.

Site number	Latitude/longitude	Elevation		Aspect	Vegetation	Other site characteristics
		(ft)	(m)			
1	47°05'14"N/69°01'30"W	610	190	Level	Cleared	Adjacent to met station
3	47°06'17"N/69°09'30"W	1000	300	North	Softwoods	9% slope, sheltered, closed canopy
4	47°07'19"N/69°06'40"W	650	200	Level	Softwoods	Sheltered, 90% canopy cover
5	47°08'03"N/69°07'26"W	840	250	Northeast	Mixed	50% open/50% hardwoods, unsheltered
7	47°09'31"N/69°05'17"W	840	250	Southeast	Hardwoods	15-30% slope
9	47°08'38"N/69°02'49"W	900	270	Level	Cleared	Old burn scar, swampy area
10	47°03'49"N/69°08'56"W	1240	380	Southeast	Mixed	7-8% slope
11	47°03'47"N/69°09'52"W	1300	400	North	Hardwoods	3-4% slope, 50% open/50% hardwoods
12	47°04'04"N/69°11'06"W	1140	350	Level	Softwoods	Sheltered
13	47°04'44"N/69°10'28"W	880	270	Level	Cleared	Steep slope with 200-250 ft (60-75 m) rise directly east of site, sheltered from east wind
15	47°07'30"N/69°04'08"W	1450	440	Level	Mixed	Highest elevation

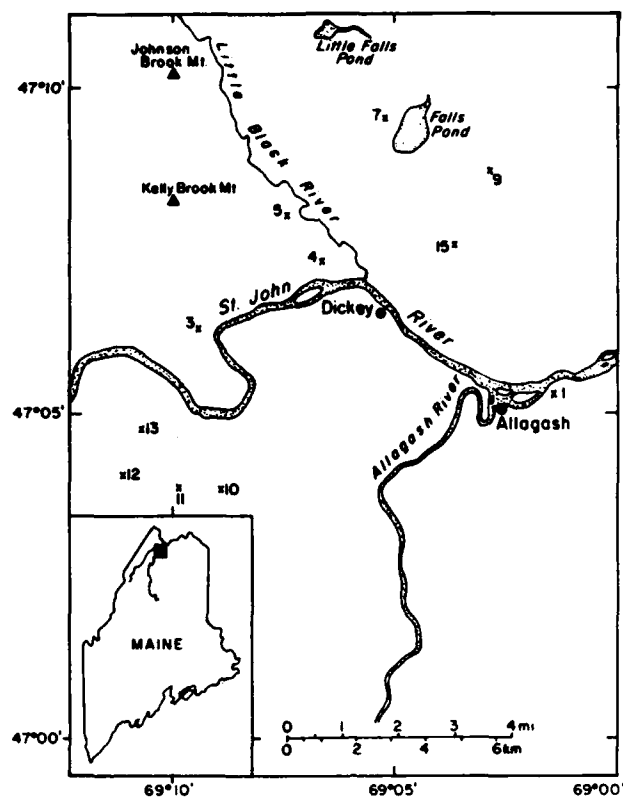


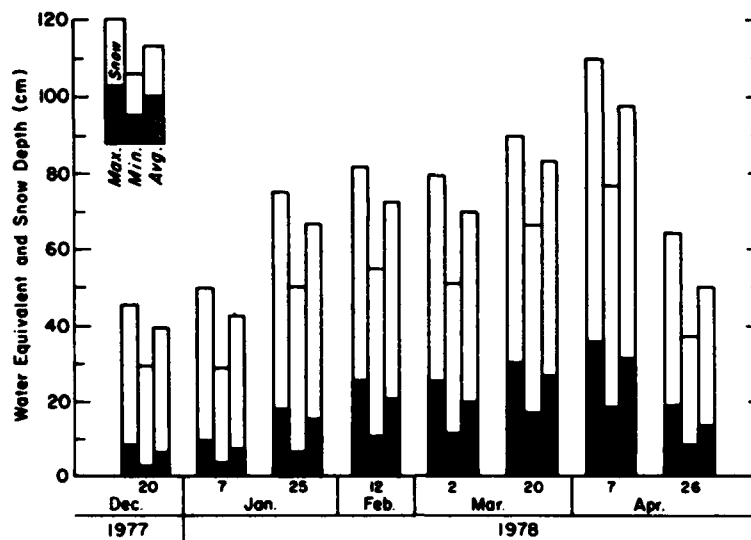
Figure 8. Locations of the 11 snow courses in the Allagash, Maine, area.

Figure 9 shows the maximum, minimum, and average values for snow depth and water equivalent for the 11 snow course sites at the time of the Landsat satellite overpasses. Detailed tables on the snow depth and water equivalent data for each snow course site are shown in Appendix A. Appendix B is a computerized listing of the daily meteorological data that was obtained during 1977-80 at the Allagash site in support of the snow cover mapping project. Additional meteorological information can be found in Bates (1983).

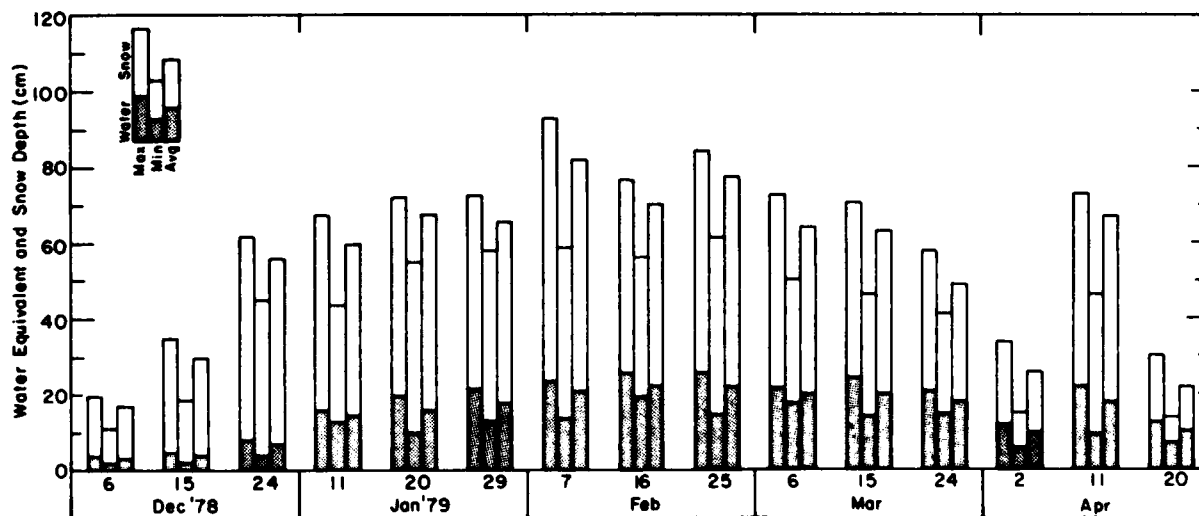
The Landsat MSS digital data were analyzed to determine whether a correlation existed between snow depth and the measured intensities in the four spectral bands. The five snow-covered Landsat scenes used in the analysis were the only ones available that were relatively cloud-free: 6 January 1978, 11 February 1978, 1 March 1978, 24 December 1978, and 11 January 1979. Histograms of the brightness values in MSS band 7 for a 300- x 300-pixel (420 km<sup>2</sup>) area located near Allagash,

Maine, were investigated. The data for the five winter scenes were registered with the assistance of a Ramtek image display unit. The 11 snow course sites were identified within the 300- x 300-pixel area. Individual band count values, band ratios, and band summations were evaluated. A solar elevation correction was also applied to account for differences in insolation for the different Landsat dates.

A scene from 31 May 1978 was used to classify the three subbasins using the GISS-MAP1 algorithm. During this season the forest types could easily be separated due to the phenological state of the deciduous trees. The young leaves of these trees showed a high near-infrared reflectance (MSS 7) in comparison with that of the evergreen forest. The land cover types classified included water, open areas, softwoods, hardwoods, and mixed forest. The selection of training sites for classification of vegetation types was aided by the use of aerial photography.



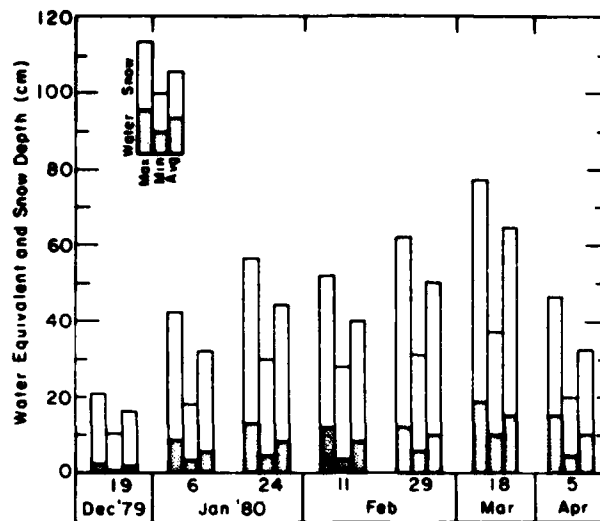
*a. 1977-78 winter season.*



*b. 1978-79 winter season.*

**Figure 9. Snow depth and water equivalent values during the Landsat overpasses.**





c. 1979-80 winter season.

Figure 9 (cont'd).

## RESULTS AND DISCUSSION

### Histogram analysis—uncorrected Landsat data

The statistical analysis of the uncorrected Landsat data indicated that a direct correlation did not exist between snow depth and the measured intensities in the four MSS spectral bands. This was true in the comparison among the various snow course sites for a single Landsat scene and among the various Landsat scenes for individual snow course sites.

Although the Landsat reflected-radiance values measured for a single pixel (0.45 hectare) did not increase (or decrease) uniformly with increasing snow depth, it was hypothesized that on a regional scale ( $> 26 \text{ km}^2$ ) changes in overall brightness might occur. To test this hypothesis, histograms of the MSS 5 and 7 data were examined for the five winter scenes, the 31 May 78 scene, and an autumn scene from 27 October 1977.

The MSS bands 5 and 7 count histograms for the five land-cover classes and the total area for each of the six Landsat scenes are shown in Figures 10. The count values for MSS 5 range from 0 to 127 and for MSS 7 range from 0 to 63. Although the number of pixels varies from class to class due to the nature of the study site, the number of pix-

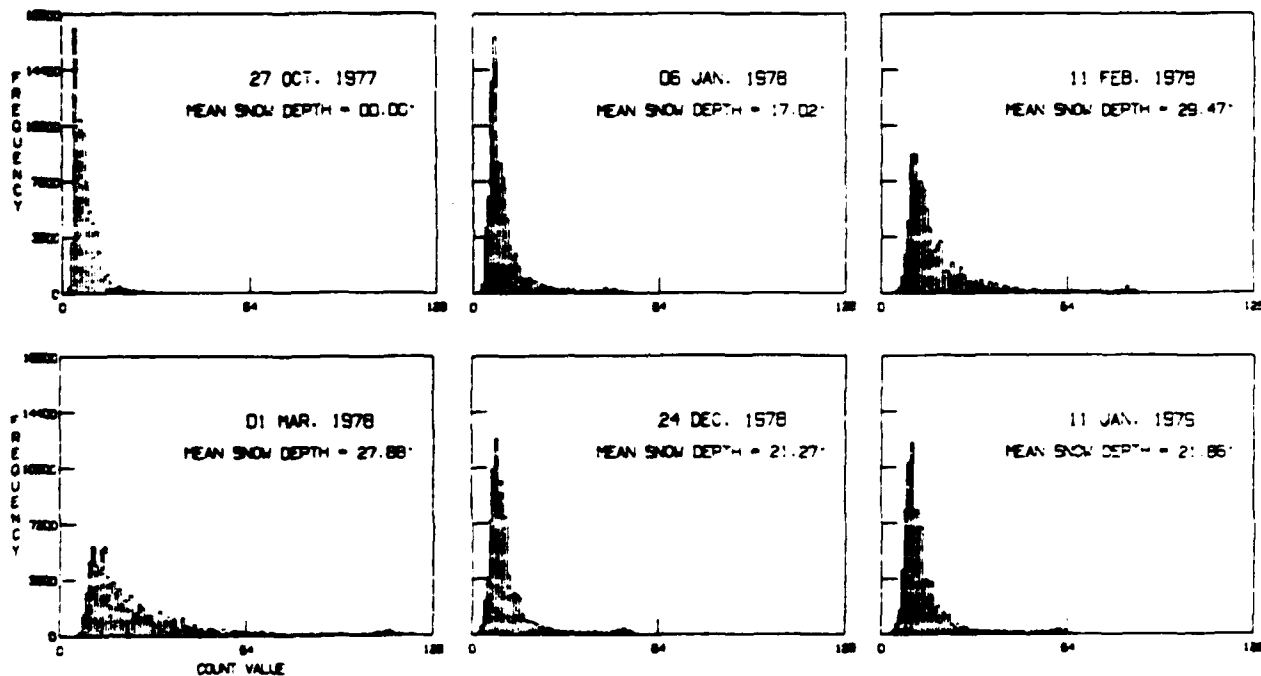
els within any class remains constant from one observation date to another. Much of the skewness observed in the regional histograms appears to result from the water and open area pixels. This is particularly noticeable for water surfaces because the absorption characteristic of water is replaced by an open expanse of highly reflective ice and snow cover.

For the forest cover classes, the shift in histogram shape is less dramatic. For the softwoods class there is little noticeable change in the shape or dimensions of the histogram between the Landsat winter scenes and the 27 Oct 77 scene. Albedo investigations have shown that the more complete closure of the softwood canopy precludes significant reflectivity changes with a snowpack (Leonard and Eschner 1968). The histograms for the hardwoods and mixed forest show a decrease in kurtosis and a change of the histogram mode to the brighter count values as the snow depth increases.

The MSS band 7 data were used to avoid the saturation of the MSS sensor that occurred in the other multispectral bands under snow conditions. In addition, the use of MSS 7 avoided the effects resulting from the decompression of MSS bands 4, 5, and 6 that is applied during ground image processing of the Landsat data. The vegetation and

# HISTOGRAM: BAND 5

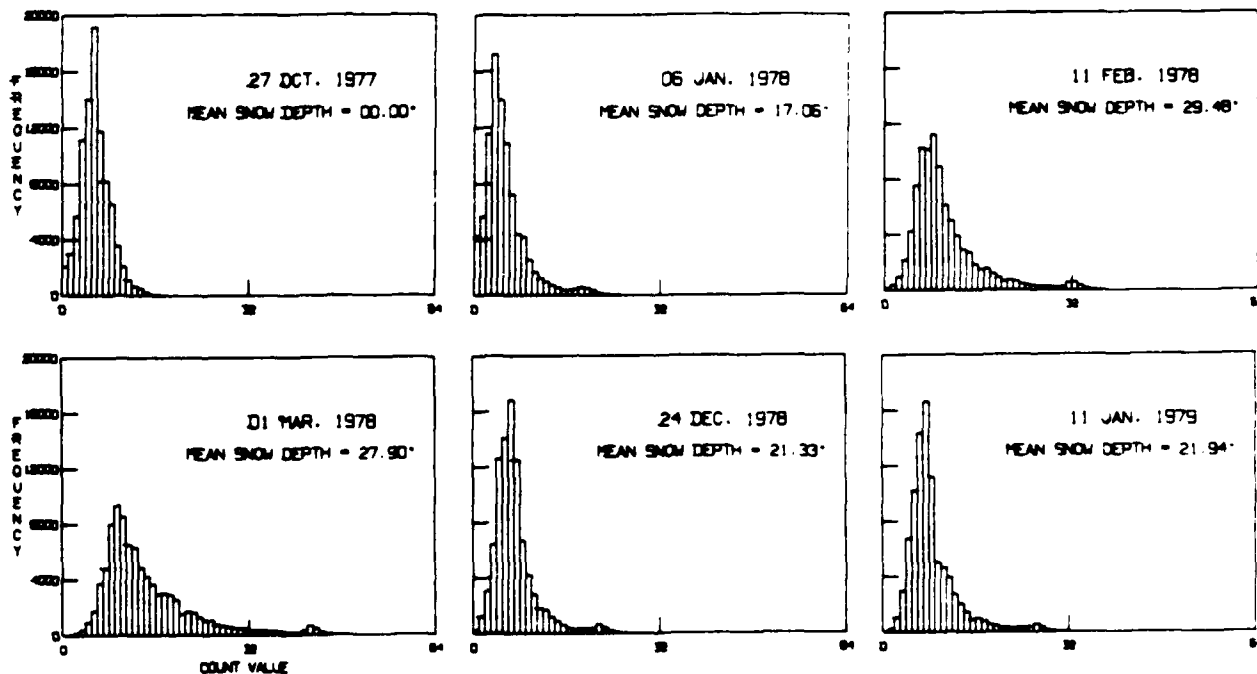
## TOTAL AREA



### a. MSS band 5.

# HISTOGRAM: BAND 7

## TOTAL AREA

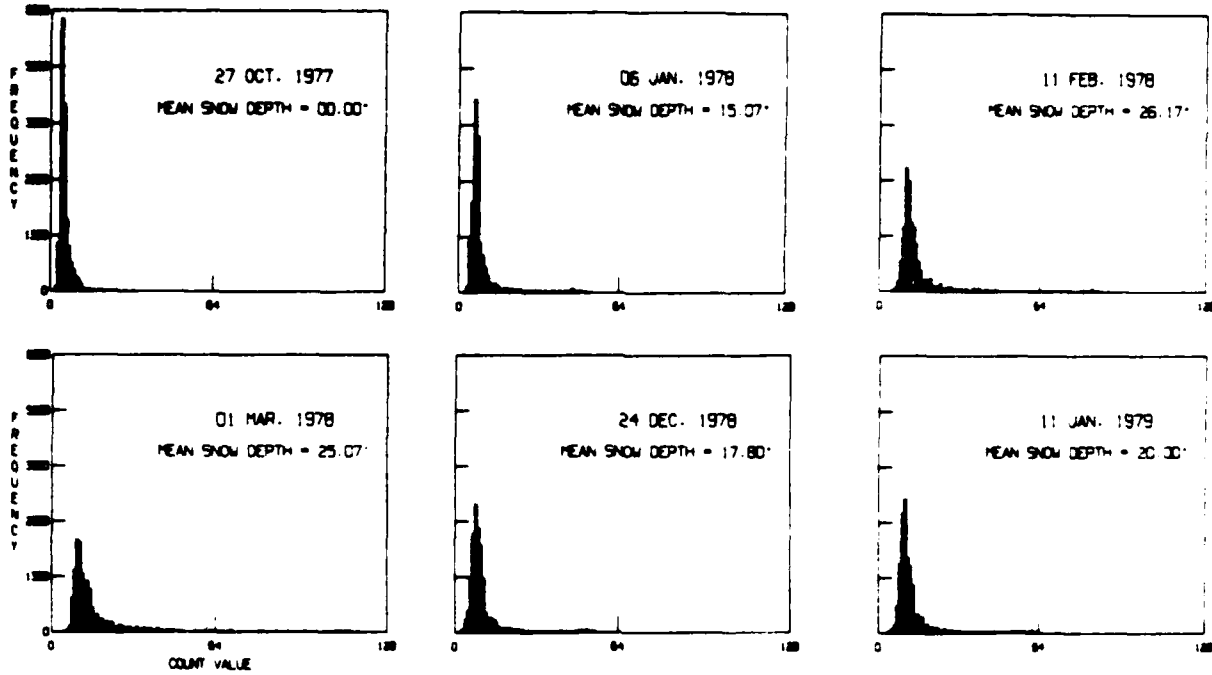


### b. MSS band 7.

Figure 10. Landsat histograms for the total area of the 300- x 300-pixel area located near Allagash, Maine.

# HISTOGRAM: BAND 5

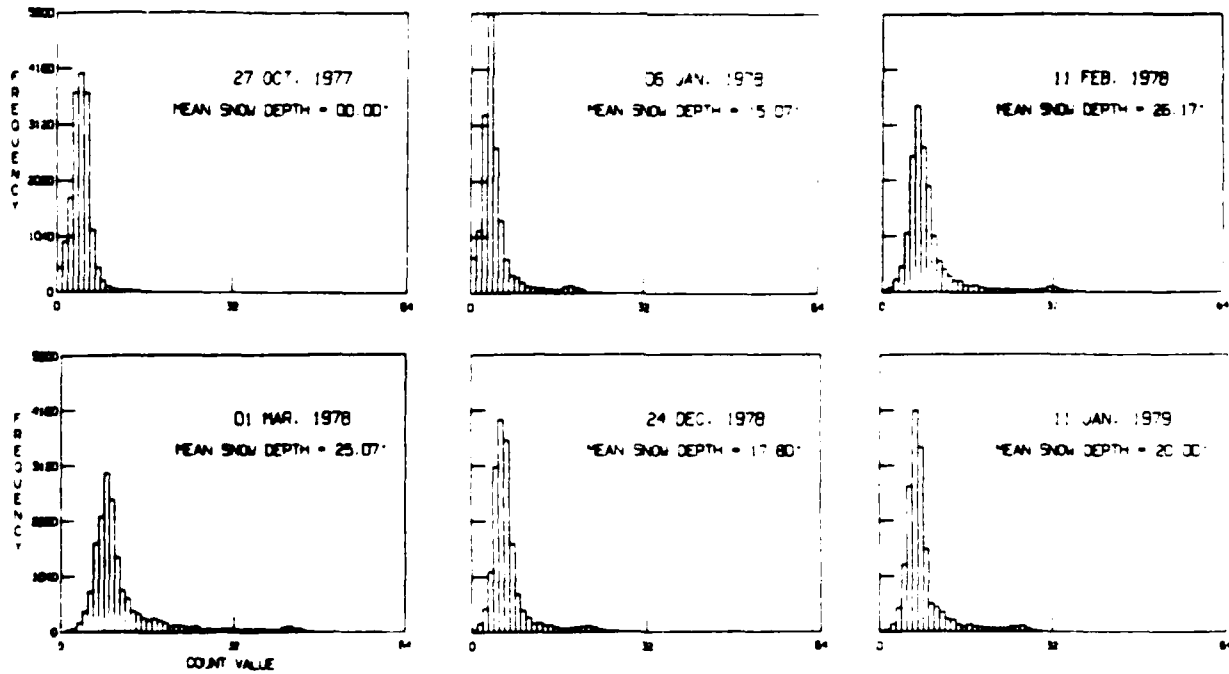
## EVERGREEN FOREST



### a. MSS band 5.

# HISTOGRAM: BAND 7

## EVERGREEN FOREST

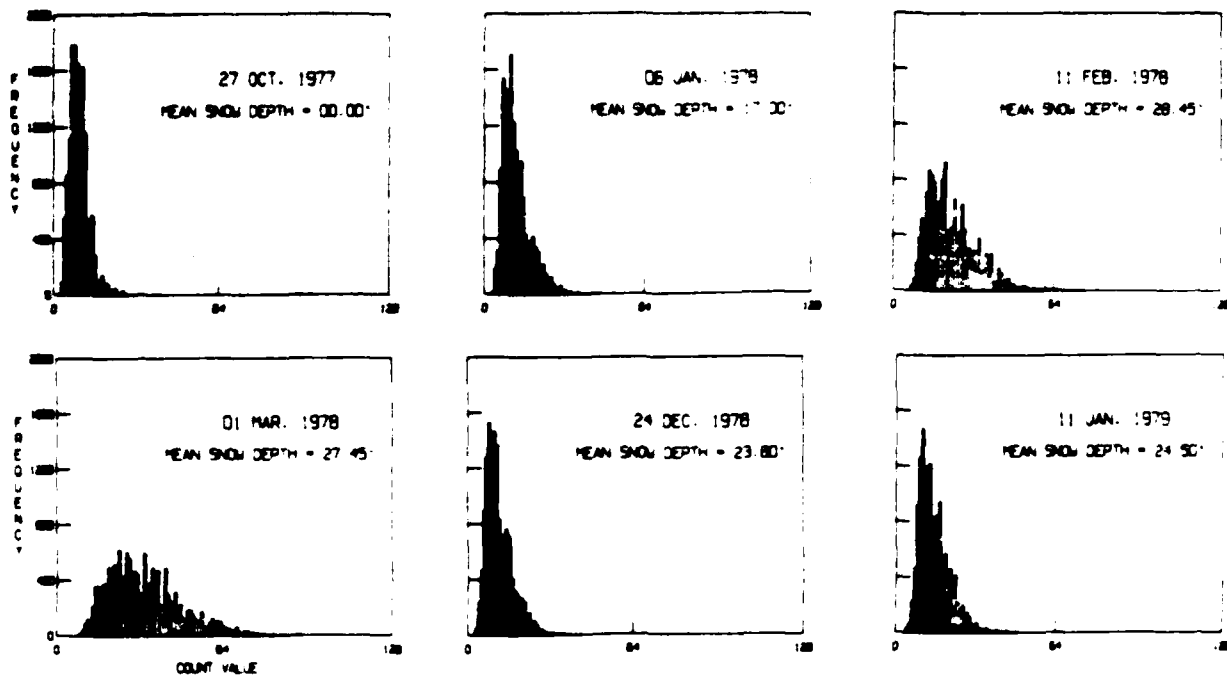


### b. MSS band 7.

Figure 11. Landsat histograms for the softwoods class.

# HISTOGRAM: BAND 5

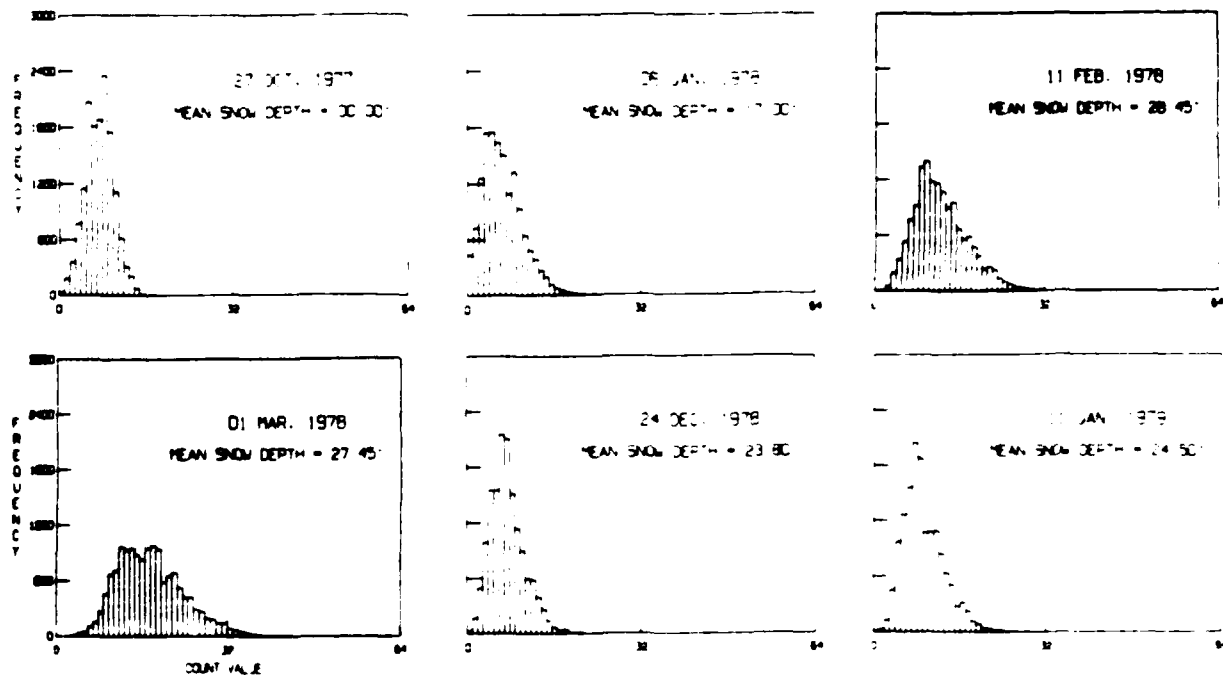
## DECIDUOUS FOREST



a. MSS band 5.

# HISTOGRAM: BAND 7

## DECIDUOUS FOREST

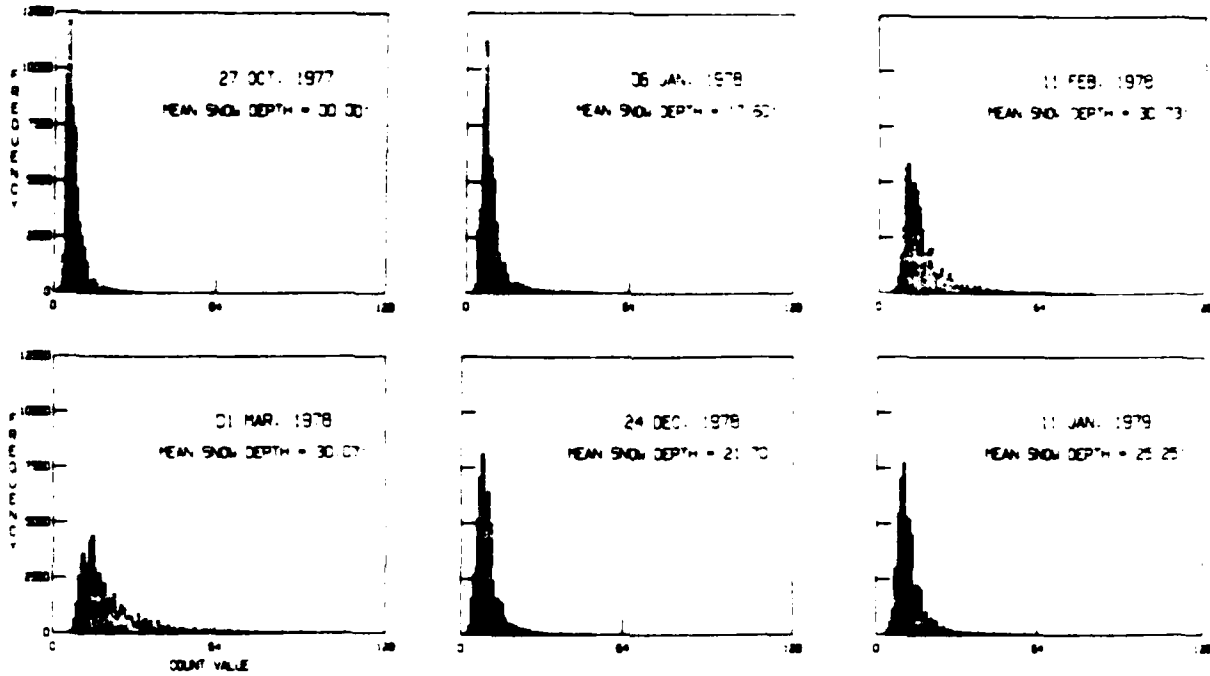


b. MSS band 7.

Figure 12. Landsat histograms for the hardwoods class.

# HISTOGRAM: BAND 5

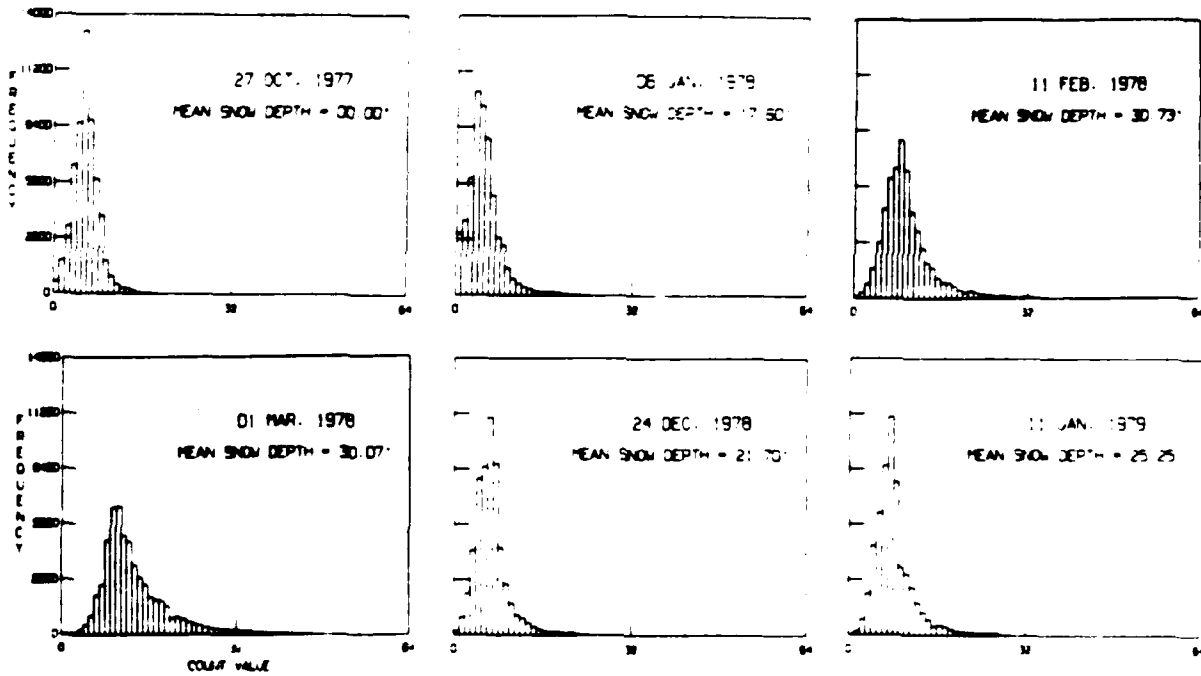
## MIXED FOREST



a. MSS band 5.

# HISTOGRAM: BAND 7

## MIXED FOREST

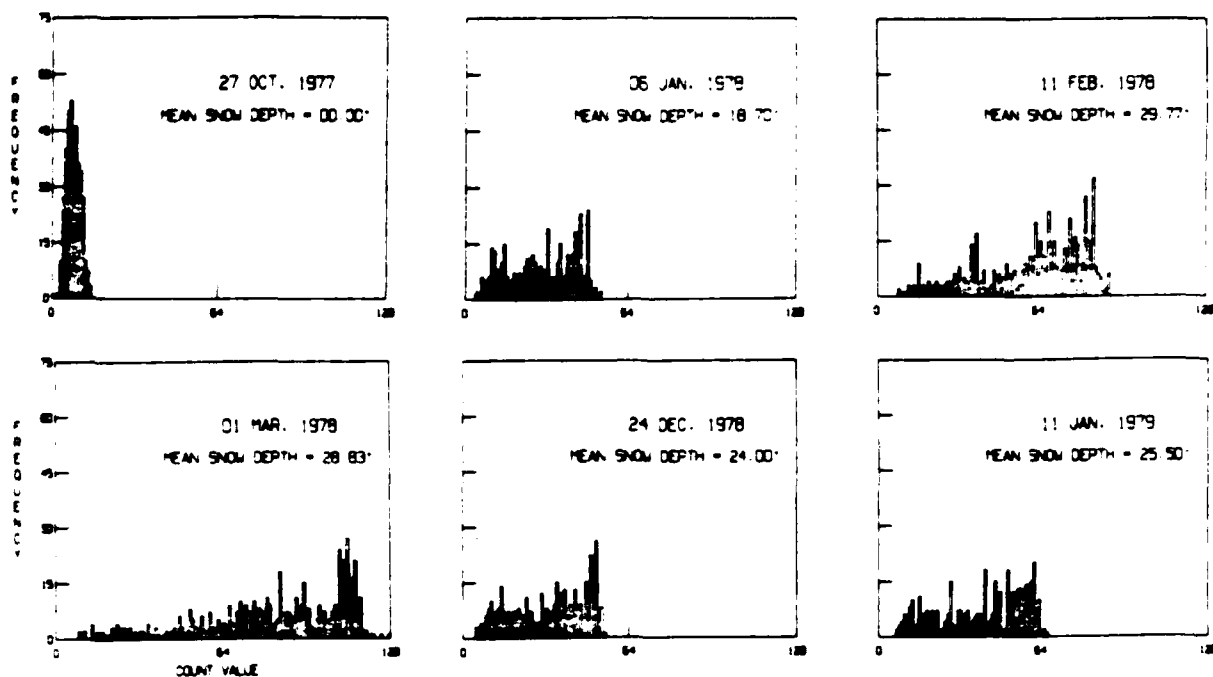


b. MSS band 7.

Figure 13. Landsat histograms for the mixed forest class.

# HISTOGRAM: BAND 5

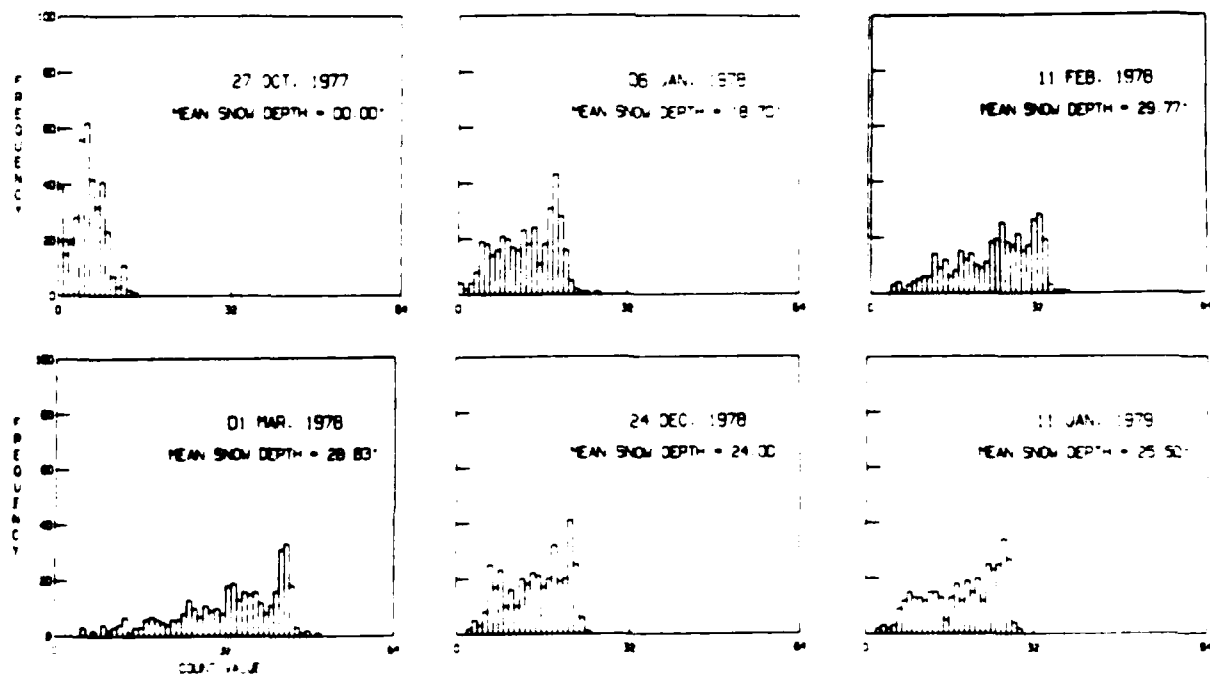
## OPEN AREAS



a. MSS band 5.

# HISTOGRAM: BAND 7

## OPEN AREAS

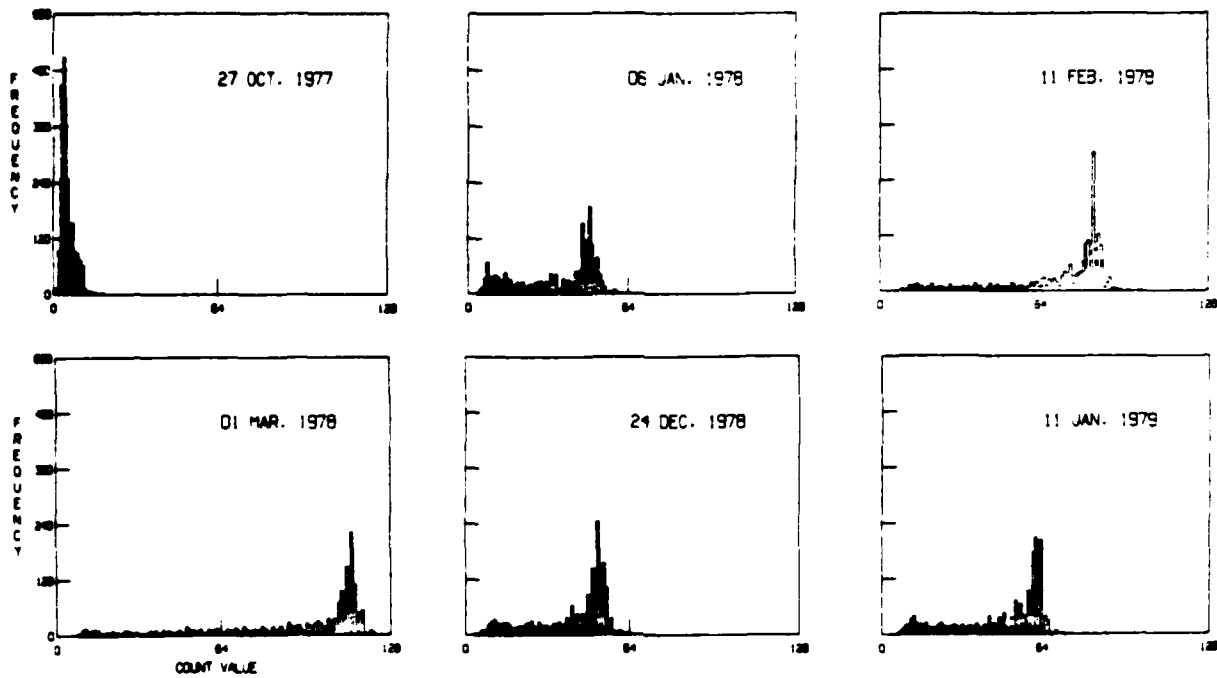


b. MSS band 7.

Figure 14. Landsat histograms for the open areas class.

# HISTOGRAM: BAND 5

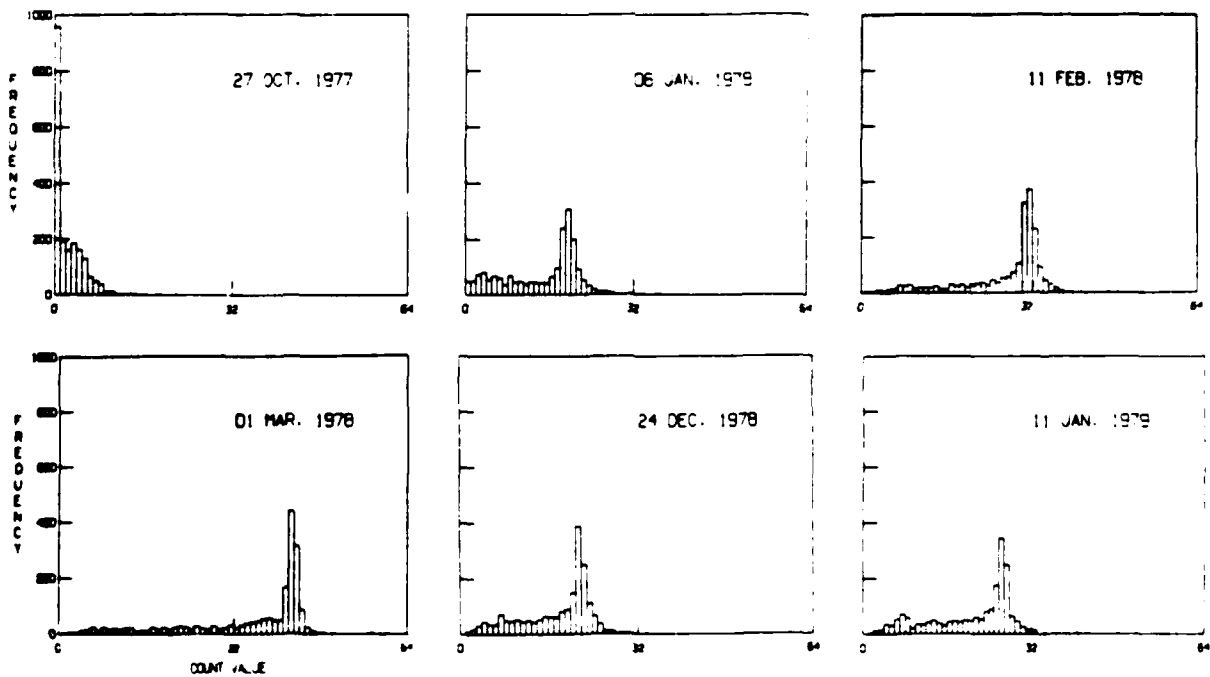
## WATER



*a. MSS band 5.*

# HISTOGRAM: BAND 7

## WATER



*b. MSS band 7.*

*Figure 15. Landsat histograms for the water class.*

low sun elevation of the 27 Oct 77 scene made it similar to winter conditions, but without snow. The histogram of the 27 Oct 77 Landsat scene exhibits a unimodal distribution with low variance (Fig. 12). As snow depth increases over the total landscape, there is a decrease in kurtosis and a corresponding increase of skewness toward the bright end of the histogram. One explanation is that as snow depth in a landscape increases throughout a snow season, the reflectance within a pixel increases with additional accumulations of snow. This results in a migration of the regional histogram from the snowless vegetation cluster of 27 Oct 77 to the brighter snow intensities observed in the Landsat winter scenes.

To quantify this observed change in histogram shape, a snow index ( $I_s$ ) was developed based on examining the various indices of skewness and kurtosis for each histogram. The equation developed was defined as:

$$I_s = a_s * \frac{\text{pop}(\text{total})}{\text{pop}(\text{mode})} * \cos(E) \quad (9)$$

in which  $I_s$  is the snow index,  $a_s$  is the moment coefficient of skewness,  $\text{pop}(\text{mode})$  is the pixel population of the histogram mode,  $\text{pop}(\text{total})$  is the total pixel population, and  $\cos(E)$  is the cosine of the solar elevation angle.

A linear regression analysis was performed with the snow index and the mean regional snow depth for the five winter scenes. The following equation was derived:

$$\text{Snow depth} = 2.079 * (I_s) - 1.111 \quad (10)$$

in which snow depth is measured in inches. The snow index,  $I_s$ , was found to predict mean snow depth with a standard error of estimate of  $\pm 2.08$  in.

Present techniques used by the Corps of Engineers, New England Division, consist of selecting representative snow courses within watersheds for Corps reservoir project areas. The data from these snow courses are used to determine an arithmetic mean of snow depth and water equivalent for that particular watershed. An error cannot be attributed to these watershed snow estimates as there is not a good data base to compare with the estimated data values. Therefore, it is assumed that the standard error of estimate of  $\pm 2$  in. would be comparable to conventional methods.

To test the snow depth analysis procedure, two additional Landsat scenes from other winter sea-

**Table 4. Landsat estimates of regional snow depth compared to available ground measurements.**

<i>Landsat estimate</i>		<i>Ground measurements</i>	
<i>Date</i>	<i>Depth (cm)</i>	<i>Date</i>	<i>Depth (cm)</i>
11 Feb 73	90.2	1 Feb 73	84.6
		19 Feb 73	96.3
19 Apr 74	40.4	16 Apr 74	60.2
		7 May 74	28.7

sons were used. Table 4 compares the Landsat estimate of snow depth with available ground measurements of snow depth taken around the Landsat pass.

#### **Histogram analysis—corrected and resampled Landsat data**

The initial results of the uncorrected Landsat data indicated that a relationship did exist between the shape of the MSS 7 histogram for an area and the depth of snow on the ground. To verify whether this effect was real or an artifact of the data, a closer examination was made of the data.

In comparing satellite observations, factors other than surface reflectivity may influence the Landsat count values used in the evaluation. In particular, atmospheric parameters (such as cloud cover), the effect of solar position, and satellite sensor characteristics may be important.

Clear sky winter conditions prevailed during all the Landsat passes. To account for variations between the three Landsat satellites and the differences in solar elevation, a transformation of Landsat counts to energy values was applied to the data:

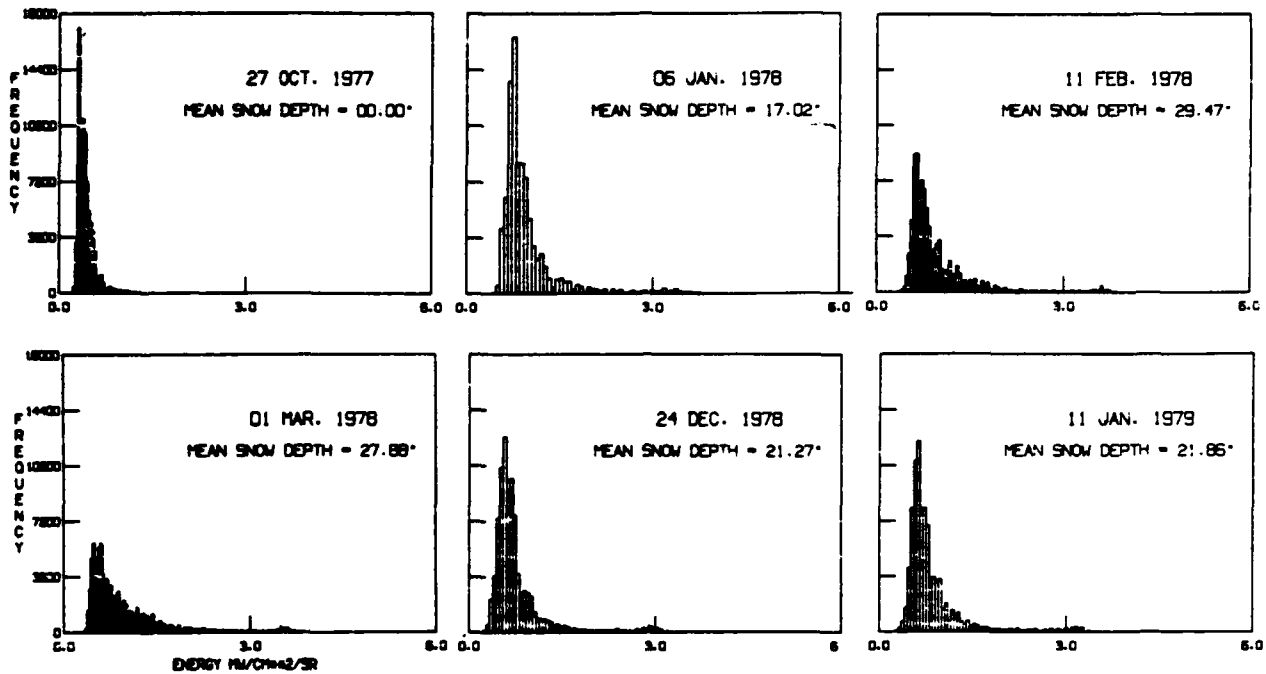
$$\text{energy} = [(\text{count} * \text{gain}) + \text{offset}] / \cos(\text{zenith}) \quad (11)$$

where energy is measured in  $\text{mW cm}^{-2}/\text{sr}$ , gain is the difference between the maximum and minimum sensitivities divided by the number of count intervals (63 or 127), offset is the minimum radiance sensitivity of the sensor and  $\cos(\text{zenith})$  is the cosine of the solar zenith angle. Table 5 shows the values of these parameters for each of the Landsat scenes.

Figures 16 through 21 are the corrected histograms for the total area and the five land cover classes for MSS bands 5 and 7. The unequal zenith

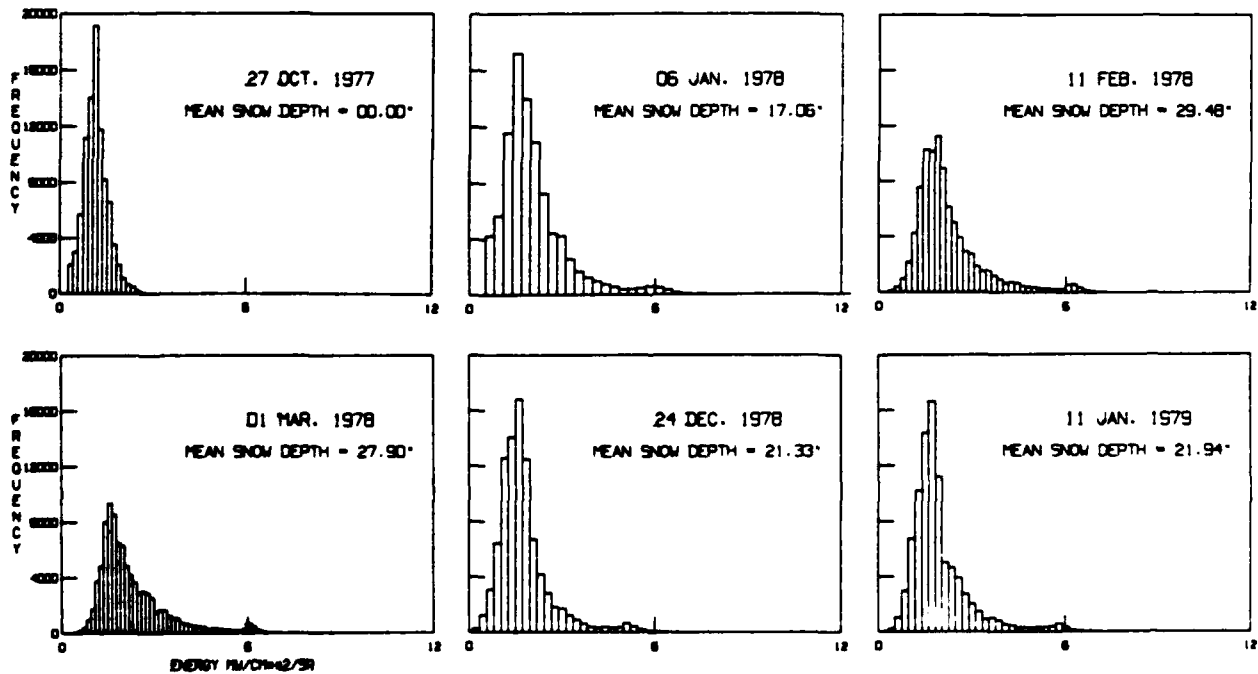


HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED  
TOTAL AREA



a. MSS band 5.

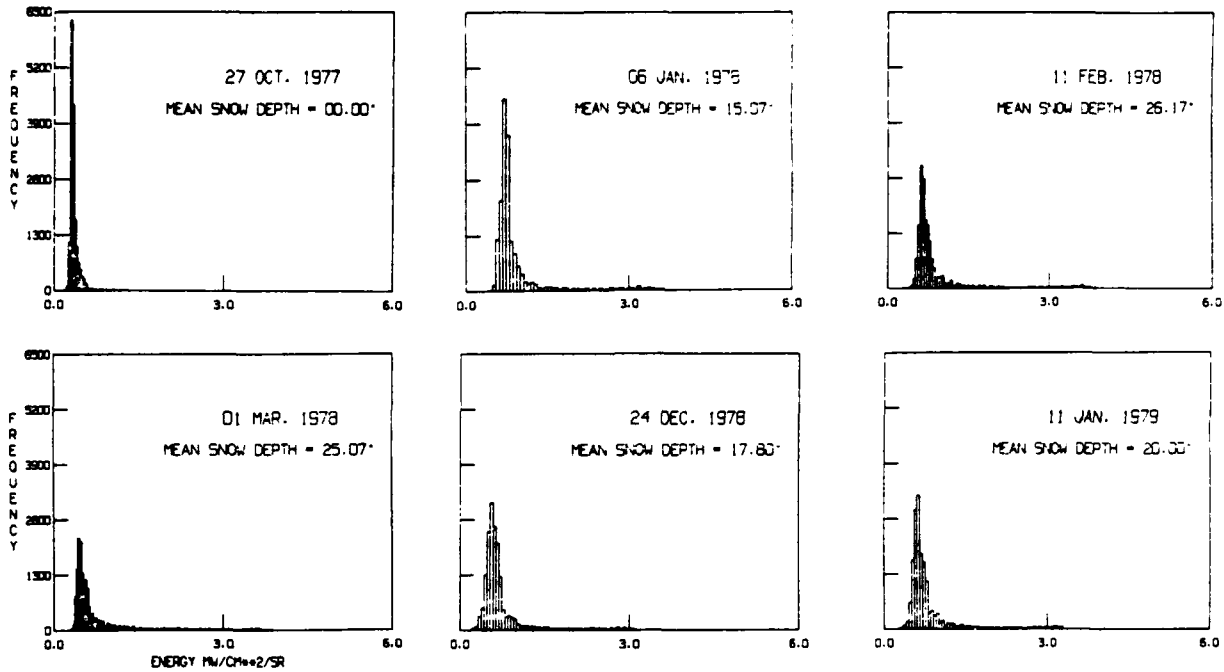
HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED  
TOTAL AREA



b. MSS band 7.

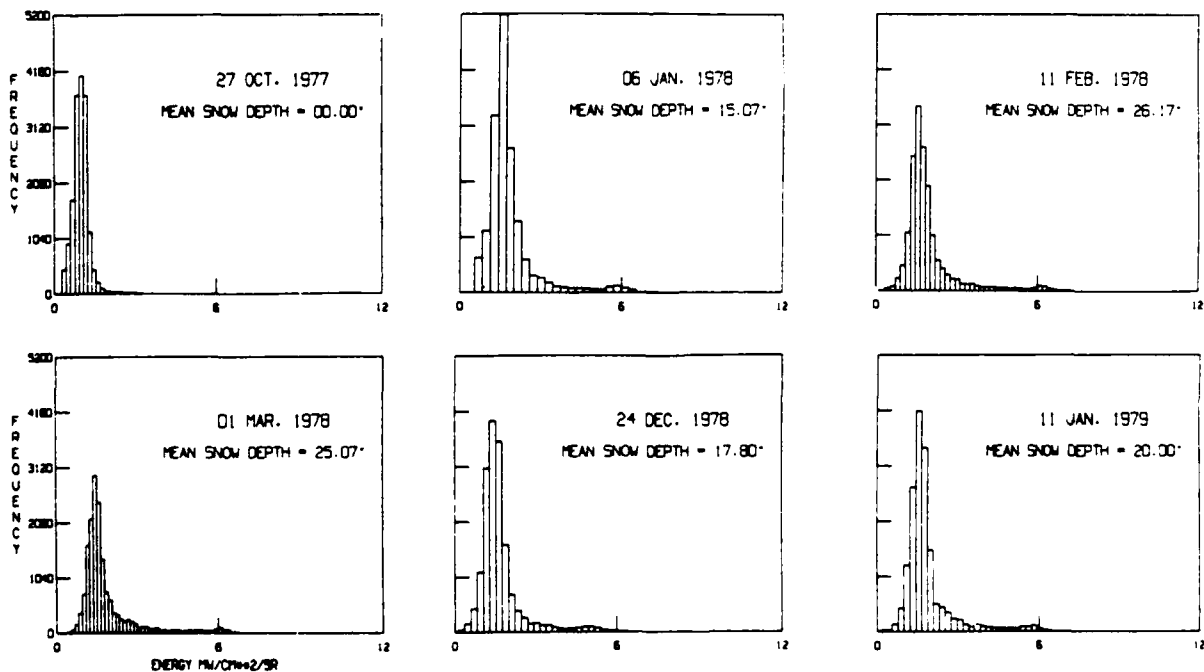
Figure 16. Landsat histograms (corrected) for the total area of the 300- × 300-pixel area located near Allagash, Maine.

HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED  
EVERGREEN FOREST



*a. MSS band 5.*

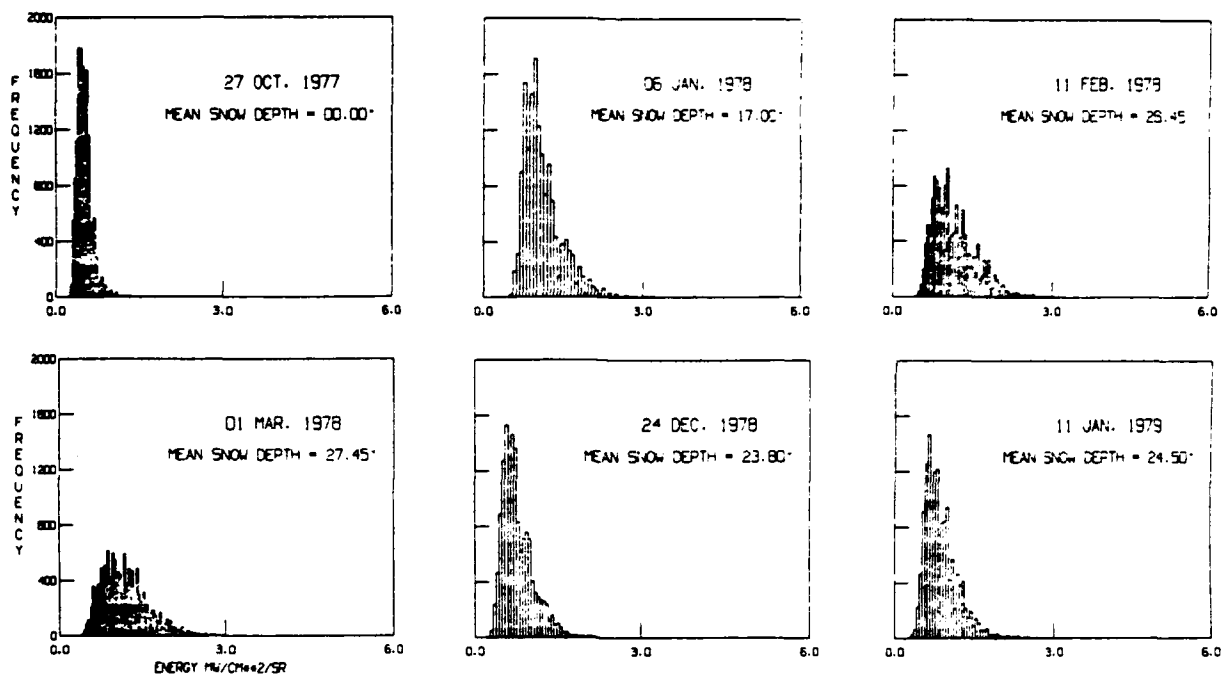
HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED  
EVERGREEN FOREST



*b. MSS band 7.*

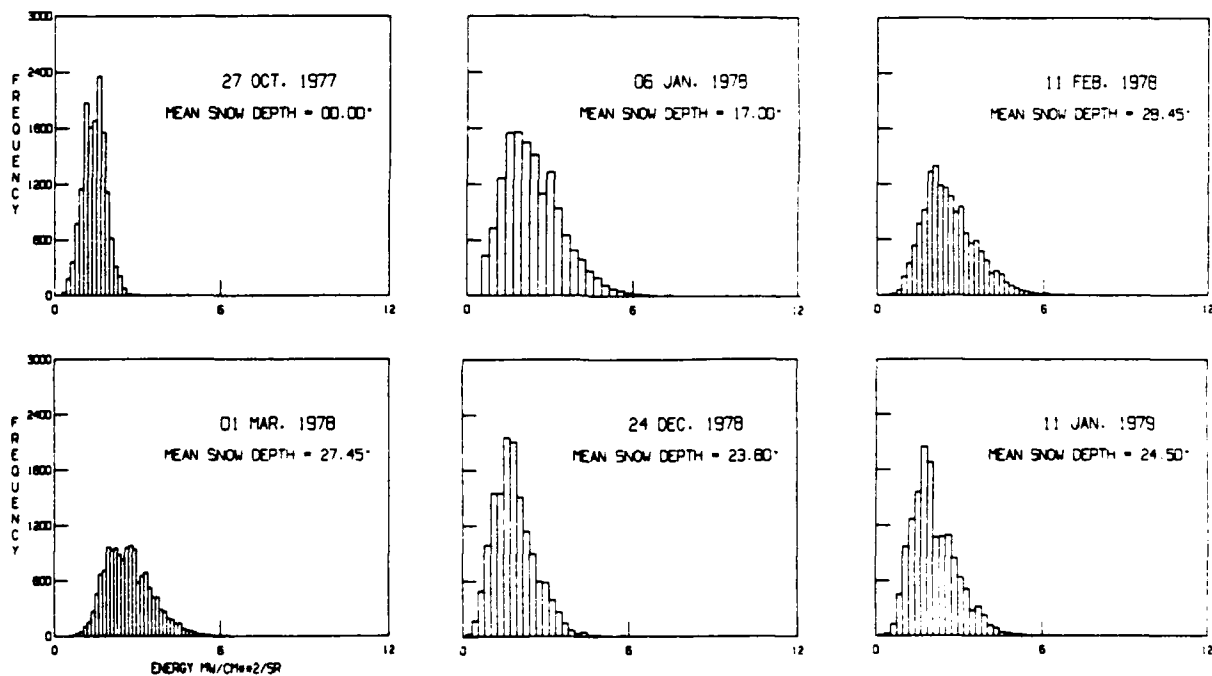
*Figure 17. Landsat histograms (corrected) for the softwoods class.*

HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED  
DECIDUOUS FOREST



*a. MSS band 5.*

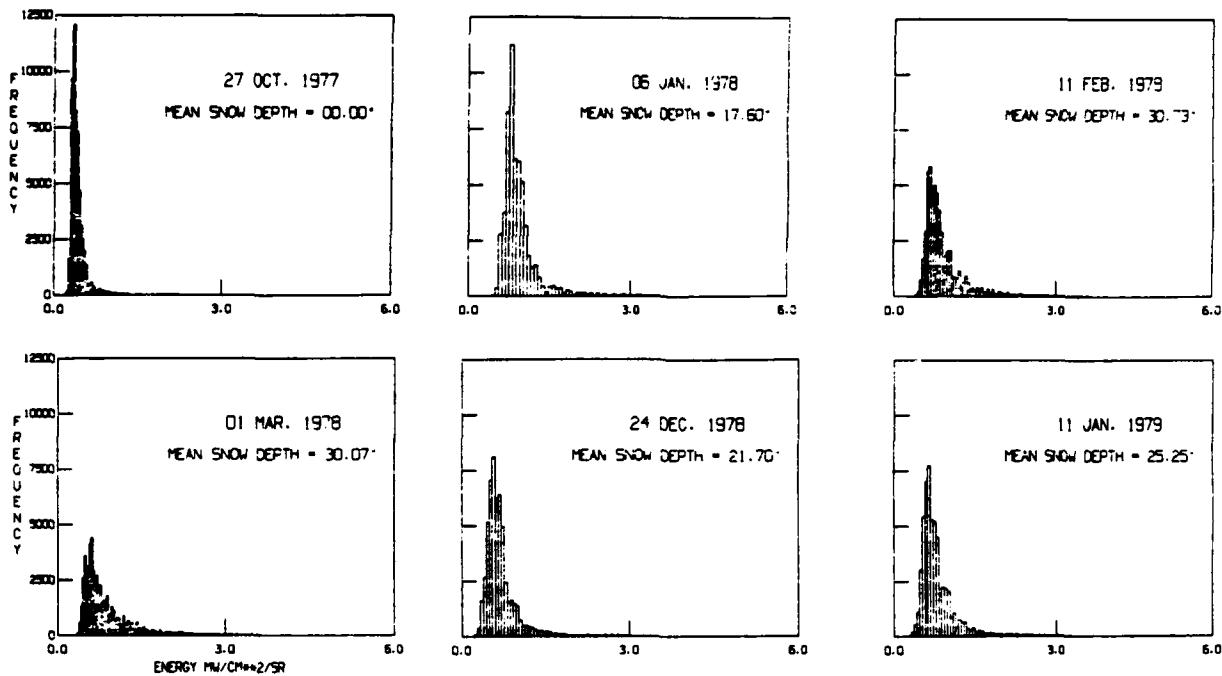
HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED  
DECIDUOUS FOREST



*b. MSS band 7.*

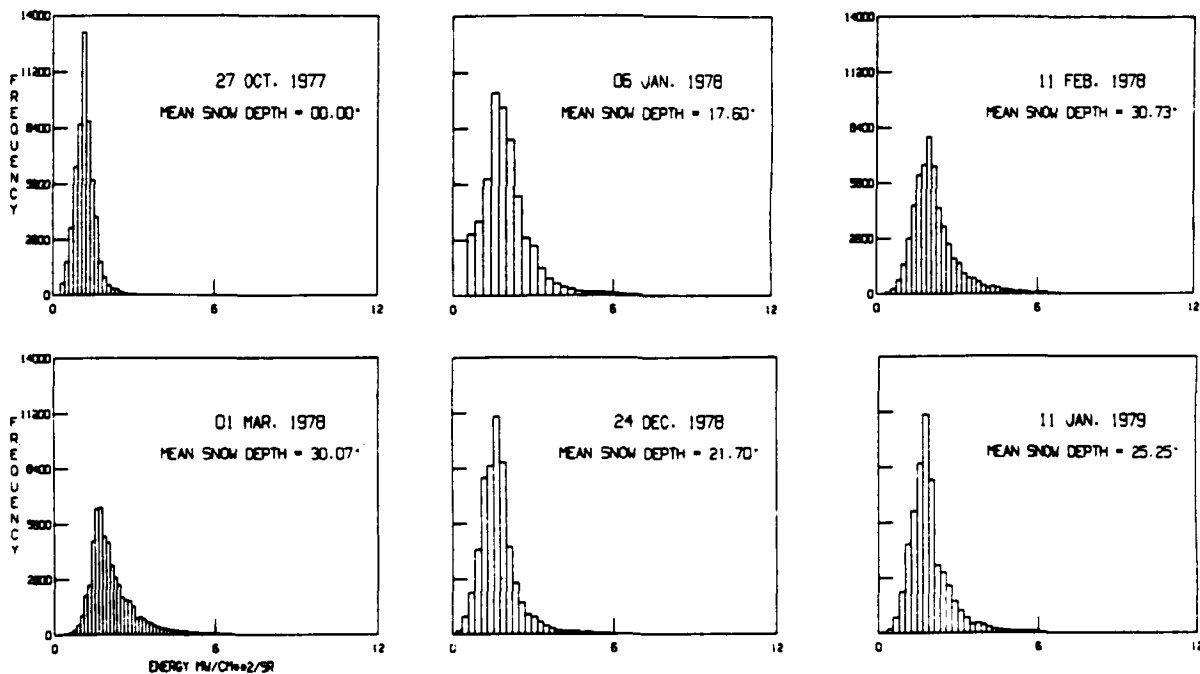
*Figure 18. Landsat histograms (corrected) for the hardwoods class.*

HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED  
MIXED FOREST



a. MSS band 5.

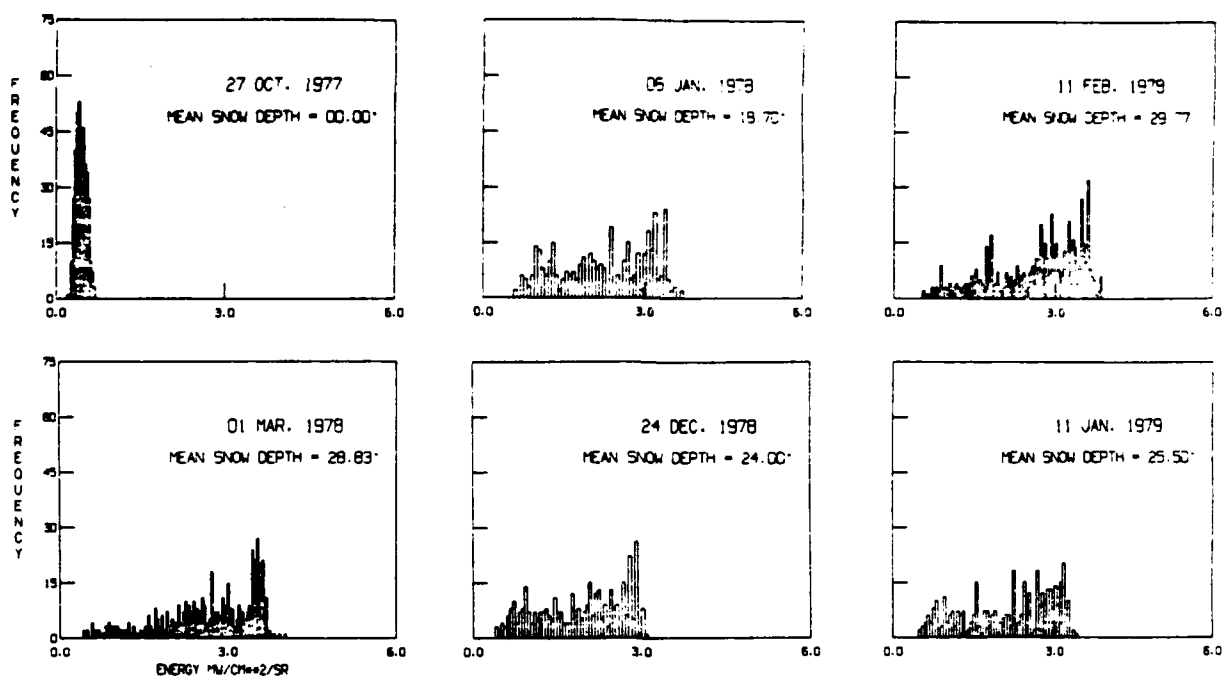
HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED  
MIXED FOREST



b. MSS band 7.

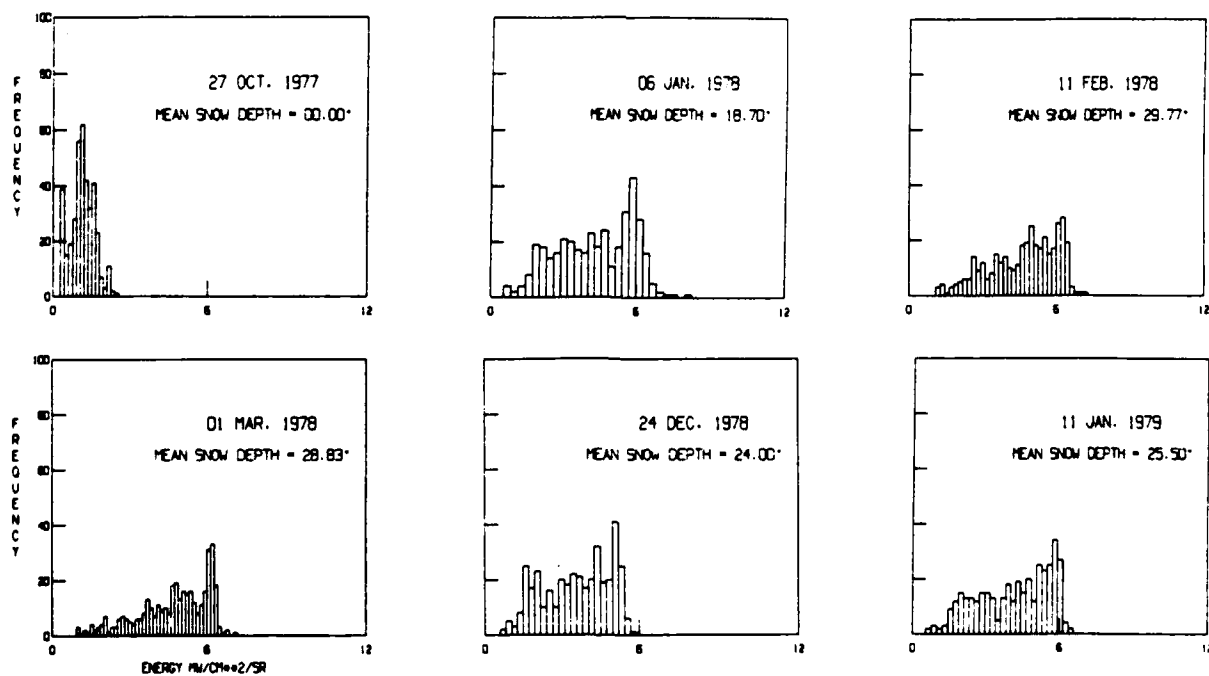
Figure 19. Landsat histograms (corrected) for the mixed forest class.

HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED  
OPEN AREAS



a. MSS band 5.

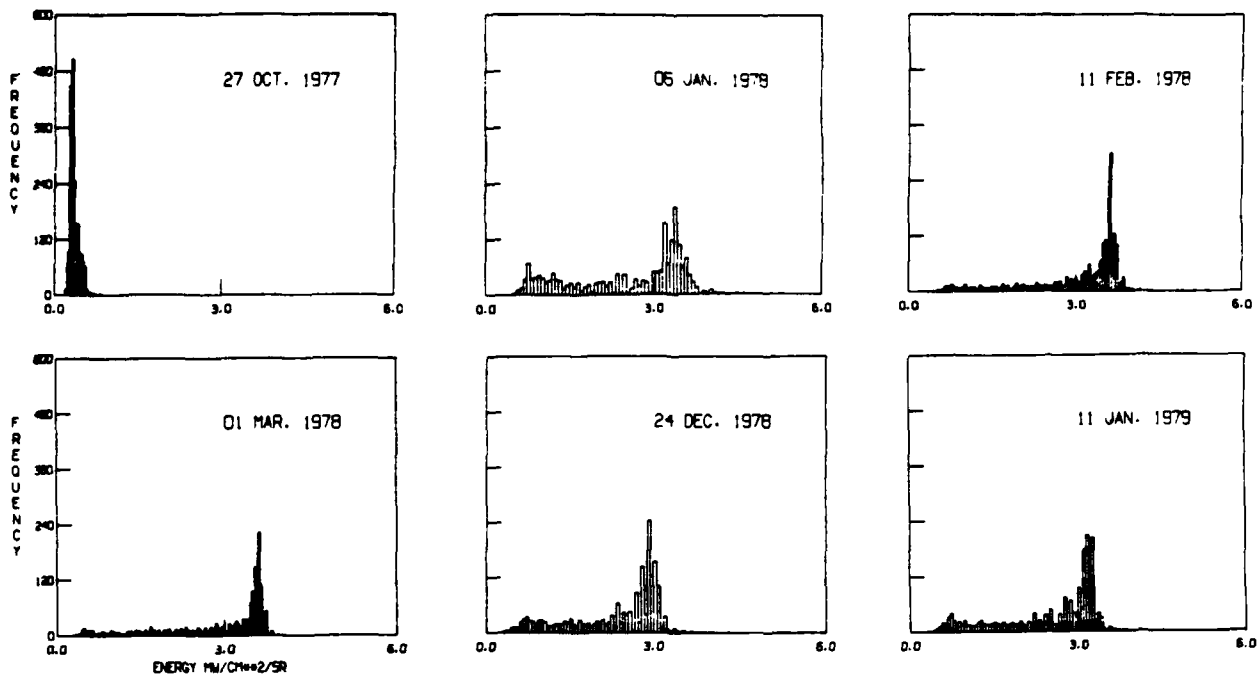
HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED  
OPEN AREAS



b. MSS band 7.

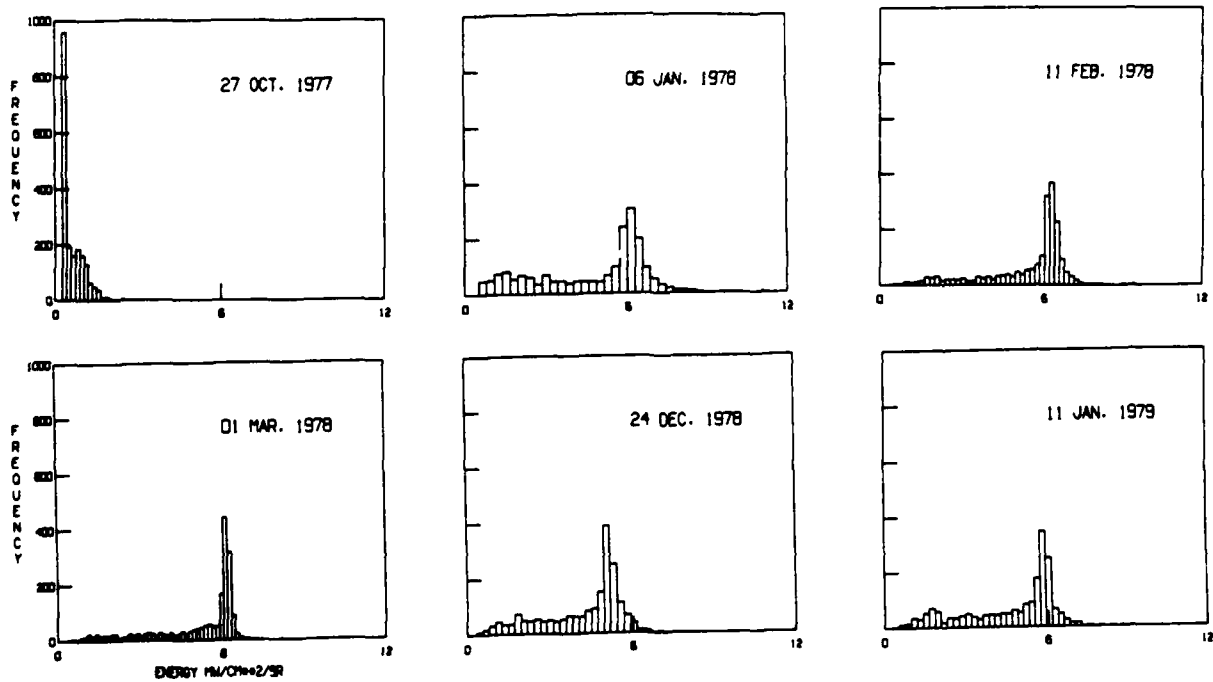
Figure 20. Landsat histograms (corrected) for the open areas class.

HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED  
WATER



*a. MSS band 5.*

HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED  
WATER



*b. MSS band 7.*

*Figure 21. Landsat histograms (corrected) for the water class.*

**Table 5. Satellite parameters used in the correction of Landsat data.**

Date	Gain		Offset		Cosine of solar zenith angle
	MSS 5	MSS 7	MSS 5	MSS 7	
27 Oct 77	0.0134	0.0603	0.06	0.11	0.3907
6 Jan 78	0.0134	0.0603	0.06	0.11	0.2079
11 Feb 78	0.0134	0.0603	0.06	0.11	0.3256
1 Mar 78	0.0134	0.0603	0.06	0.11	0.4384
31 May 78	—	—	—	—	—
24 Dec 78	0.0139	0.0603	0.03	0.03	0.2588
11 Jan 79	0.0139	0.0603	0.03	0.03	0.2756

angle of the various Landsat scenes resulted in unequal radiance levels between consecutive count values for each scene. For example, changes in one count value in the MSS 7 uncorrected data for 6 Jan 78 and 1 Mar 78 resulted in radiance changes of 0.29 and 0.138 mW cm<sup>-2</sup>/sr, respectively.

A resampling scheme was applied to correct for this radiance interval variation. The histograms were resampled to the energy levels of 6 Jan 78, the Landsat date with the lowest solar elevation angle. For 6 Jan 78 the following energy values correspond to the MSS 7 count levels:

MSS 7 count level:

0    1    2    3    4    ...    63

Radiance (mW cm<sup>-2</sup>/sr):

0.53   0.82   1.11   1.40   1.69   ...   18.80

For example, for the 1 Mar 78 scene, count level 5 corresponds to a radiance value of 0.94 and has a pixel population of 1750. Count level 5 is then resampled by weighting between levels 0.82 and 1.11 mW cm<sup>-2</sup>/sr and the pixel population is calculated using the following two equations:

$$\text{pop}_{0.82} = 1750 * \frac{1.11-0.94}{1.11-0.82} = 1026 \quad (12)$$

$$\text{pop}_{1.11} = 1750 * \frac{0.94-0.82}{1.11-0.82} = 724. \quad (13)$$

This procedure is repeated for each count level of the corrected histogram to derive the resampled histogram.

Figures 22 through 27 show the corrected and resampled histograms for MSS bands 5 and 7 for the total study area and the individual land cover classes. Within each land cover class for both

bands there is a strong similarity in the histograms on all snow-covered days.

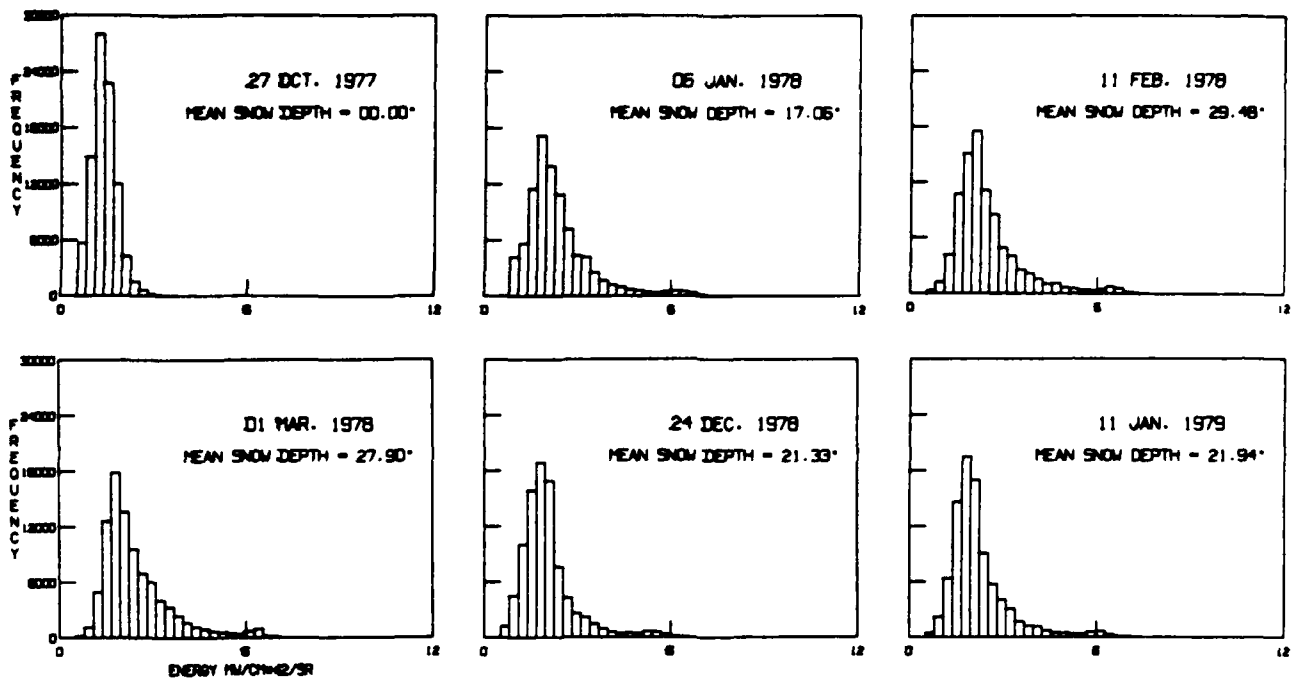
Histograms for the corrected and resampled MSS 7 data for the total area and the forested classes did not change significantly with changes in the accumulated snow depth (Fig. 22-25). A quantitative evaluation of the histograms was made and the results are shown in Tables 6 and 7. Statistics on the mean, median, mode, standard deviation, first and third quartile, 10th and 90th percentile, five indices of skewness, and three indices of kurtosis are presented. The radiance intervals between histogram levels are equal to 0.064 and 0.29 mW cm<sup>-2</sup>/sr for MSS bands 5 and 7, respectively. For the five snow days shown, three were observed with Landsat-2 (6 Jan 78, 11 Feb 78, and 1 Mar 78), while two days were observed with the Landsat-3 satellite (24 Dec 78 and 11 Jan 79). Although differences in sensor gain and offset were taken into consideration during the correction process, the Landsat-3 observations show larger energy values.

Table 8 shows the average snow depth for each land cover class and the total. These values were determined from the snow course measurements taken during the time of the Landsat overpasses.

The 31 May land cover classification was used to provide a mask with which the histograms of Landsat data could be evaluated for each of the land cover classes. Histograms for the forested landscapes, which predominate in the region, display characteristics similar to the total areas (Fig. 22-25).

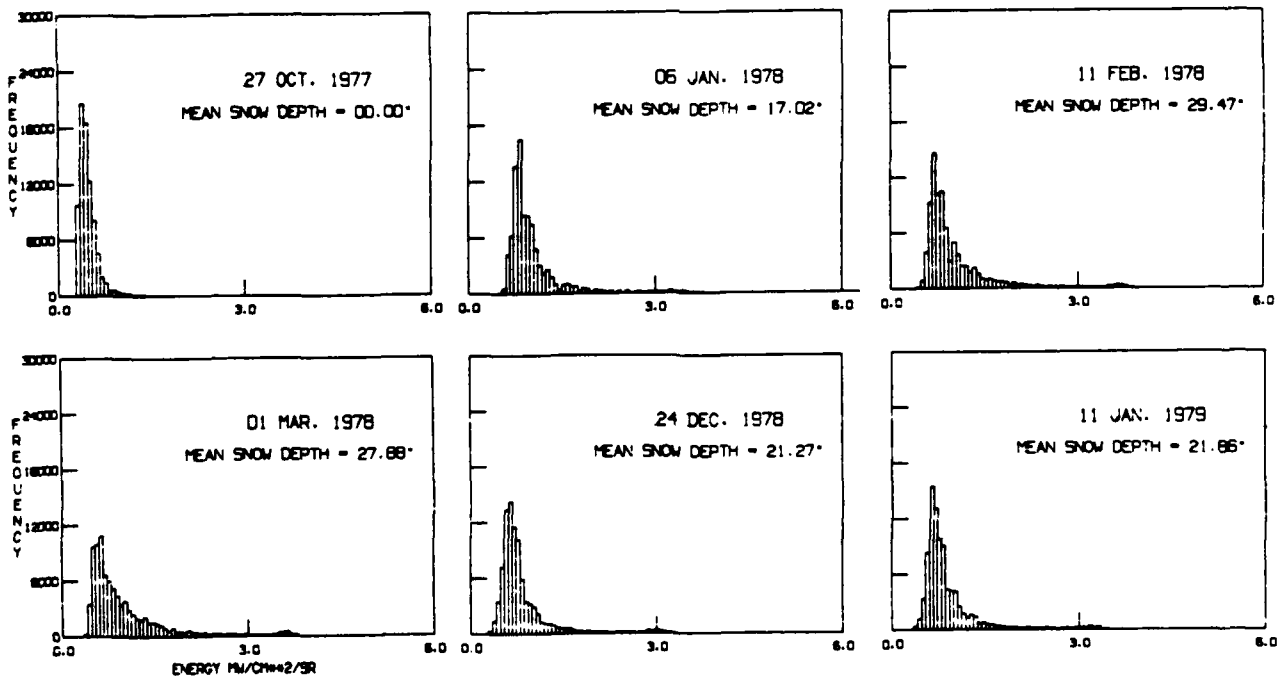
The histogram statistics for the three forest types and the total area are similar for the three winter Landsat-2 dates (Tables 6, 7). The measures of central tendency (mode) and the standard deviation (*s*) are similar. Means, quartiles, and percentiles show differences between scenes less than the radiance intervals between histogram

HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED & RESAMPLED  
TOTAL AREA



a. MSS band 5.

HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED & RESAMPLED  
TOTAL AREA

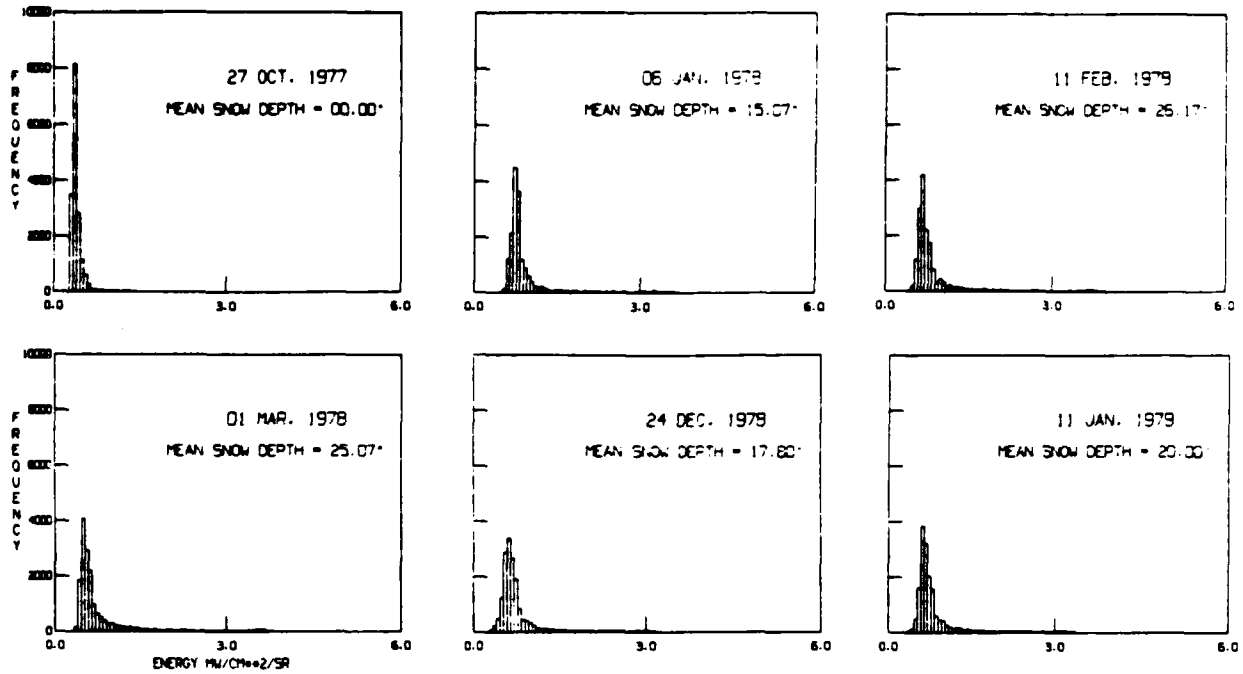


b. MSS band 7.

Figure 22. Landsat histograms (corrected and resampled) for the total 300- × 300-pixel area located near Allagash, Maine.

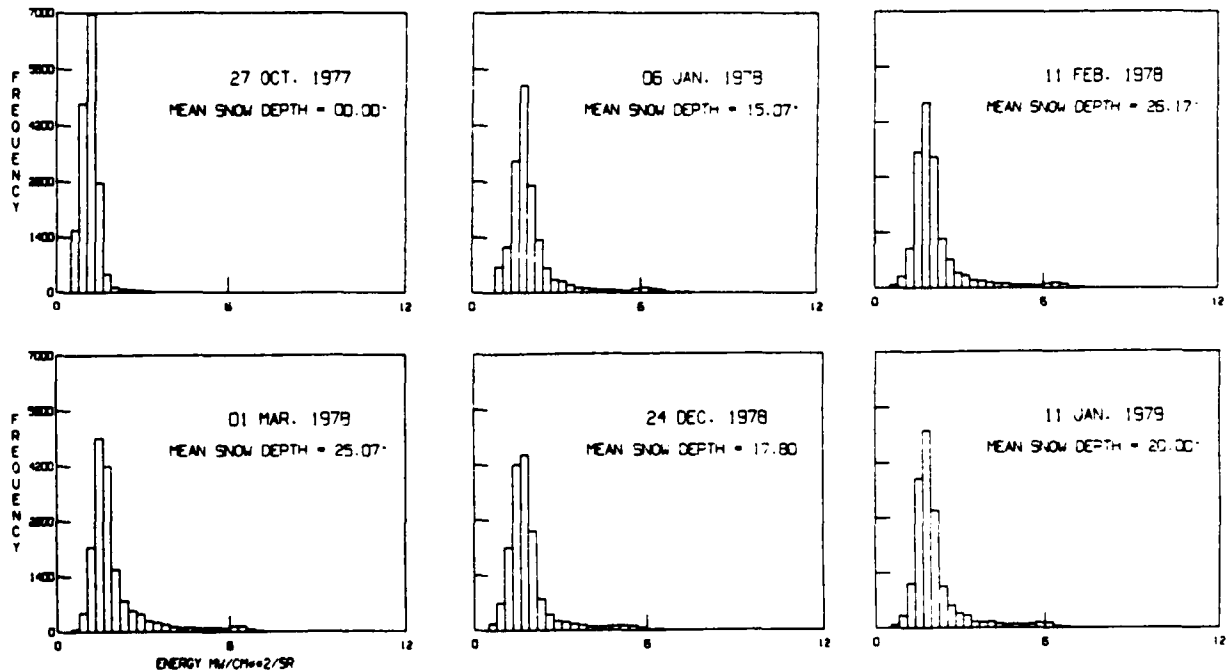


HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED & RESAMPLED  
EVERGREEN FOREST



a. MSS band 5.

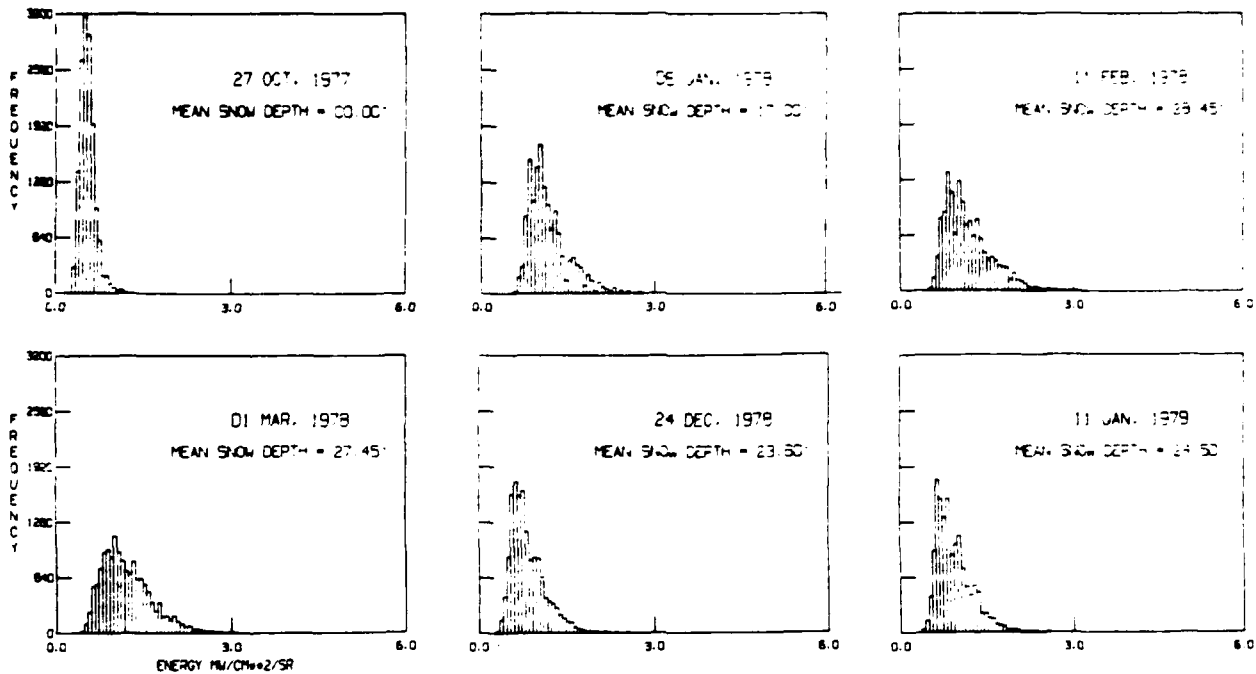
HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED & RESAMPLED  
EVERGREEN FOREST



b. MSS band 7.

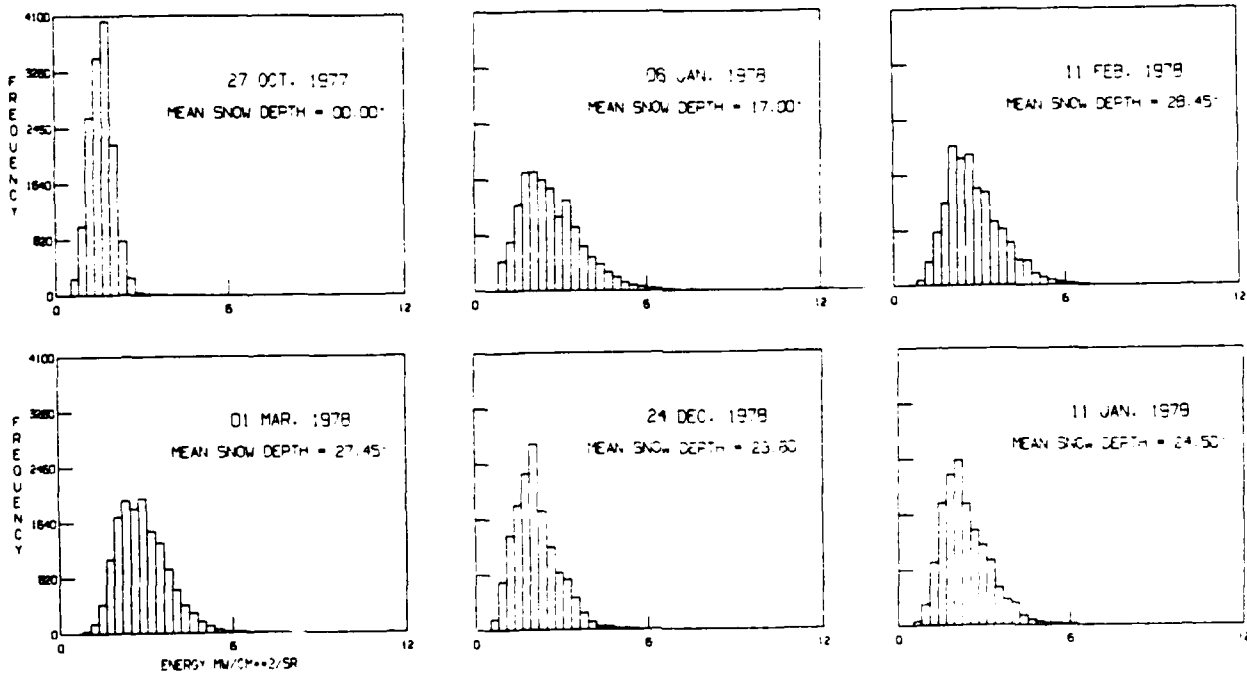
Figure 23. Landsat histograms (corrected and resampled) for the softwoods class.

HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED & RESAMPLED  
DECIDUOUS FOREST



a. MSS band 5.

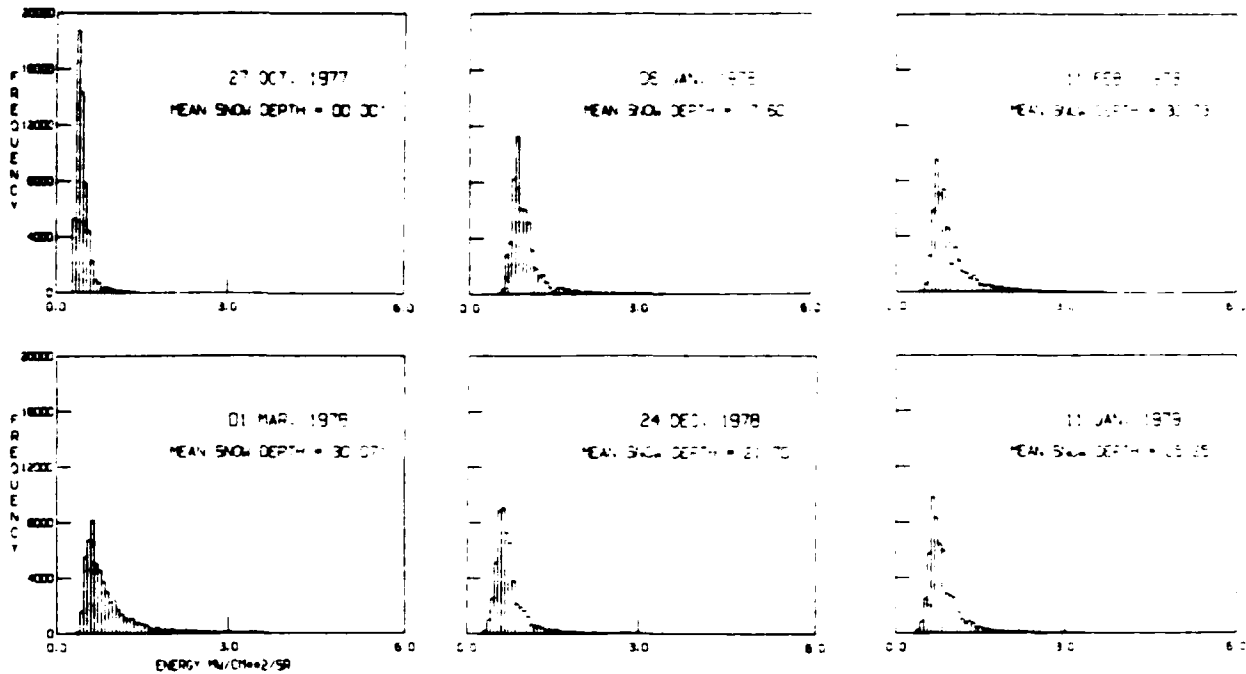
HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED & RESAMPLED  
DECIDUOUS FOREST



b. MSS band 7.

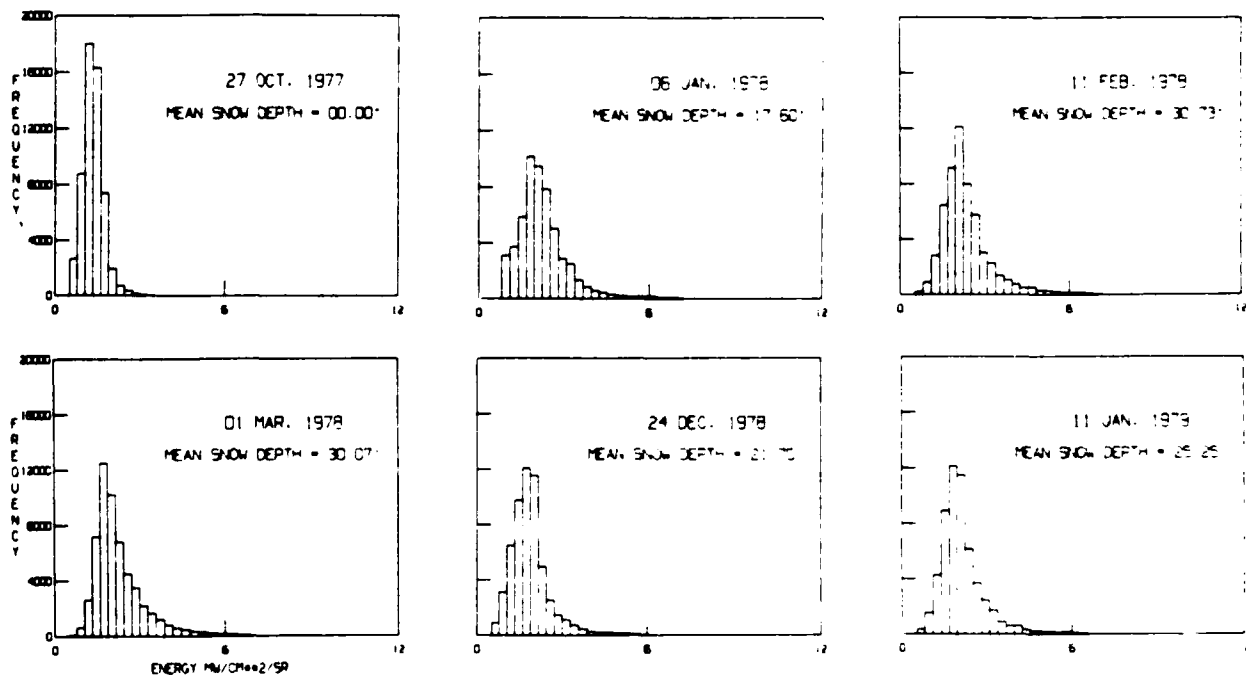
Figure 24. Landsat histograms (corrected and resampled) for the hardwoods class.

HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED & RESAMPLED  
MIXED FOREST



a. MSS band 5.

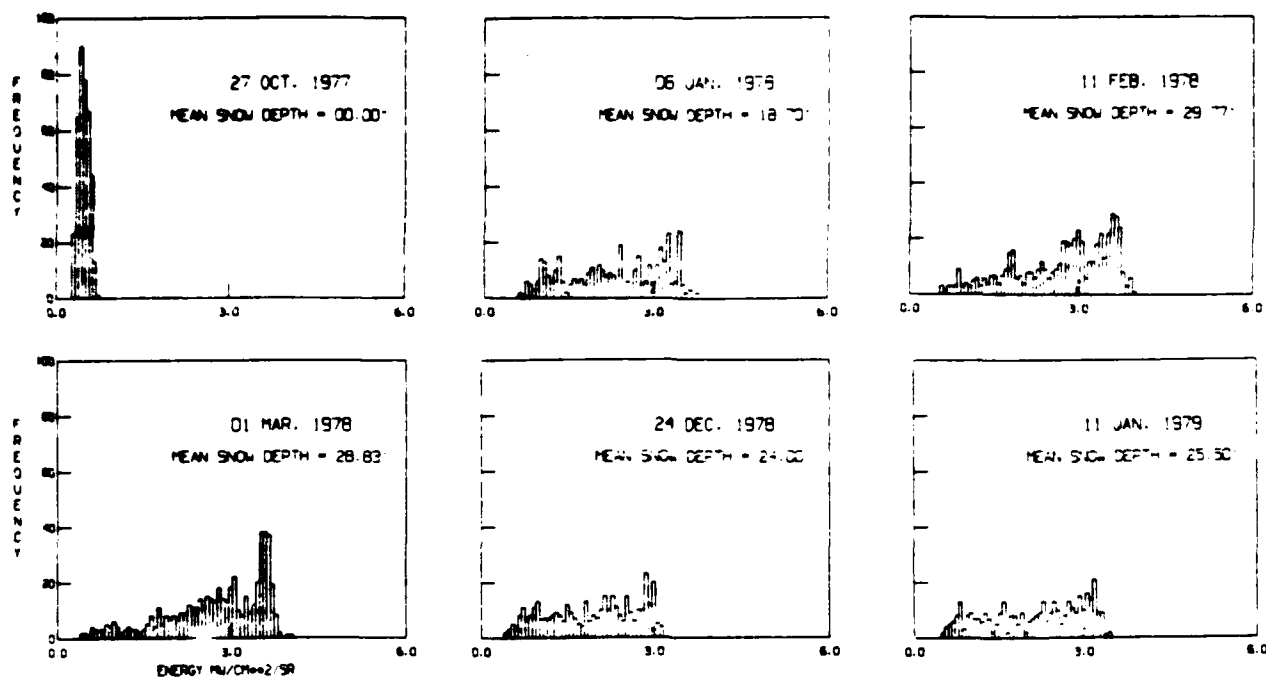
HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED & RESAMPLED  
MIXED FOREST



b. MSS band 7.

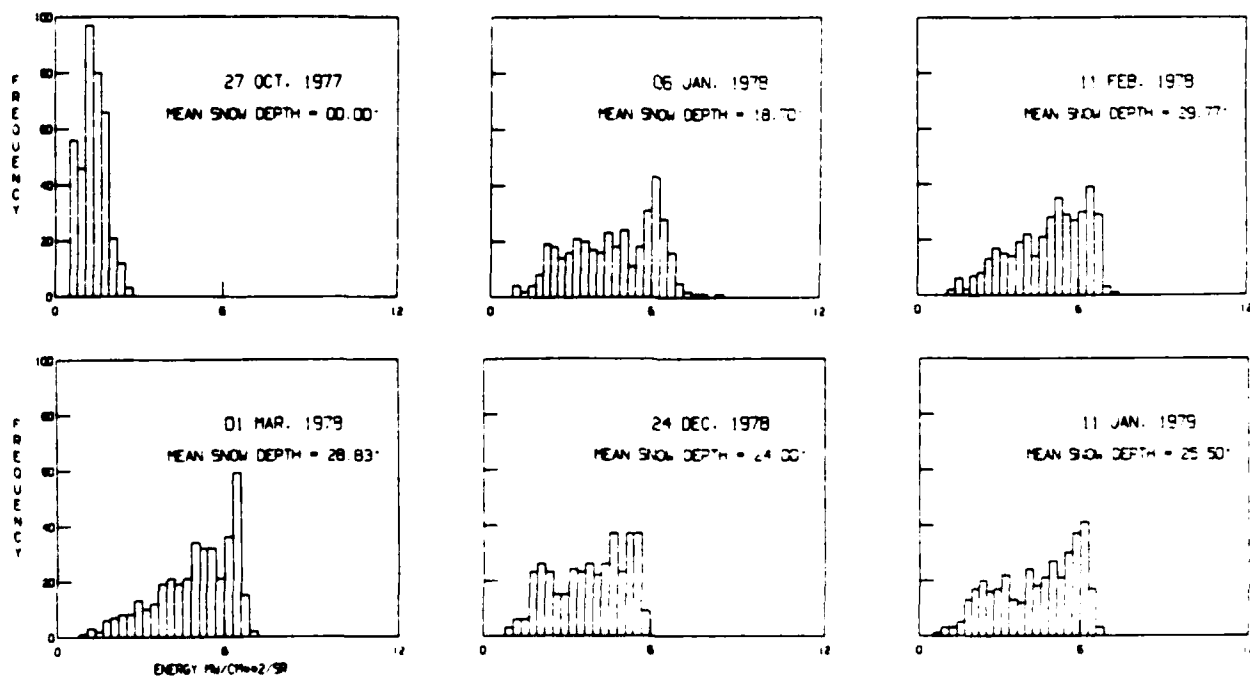
Figure 25. Landsat histograms (corrected and resampled) for the mixed forest class.

HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED & RESAMPLED  
OPEN AREAS



a. MSS band 5.

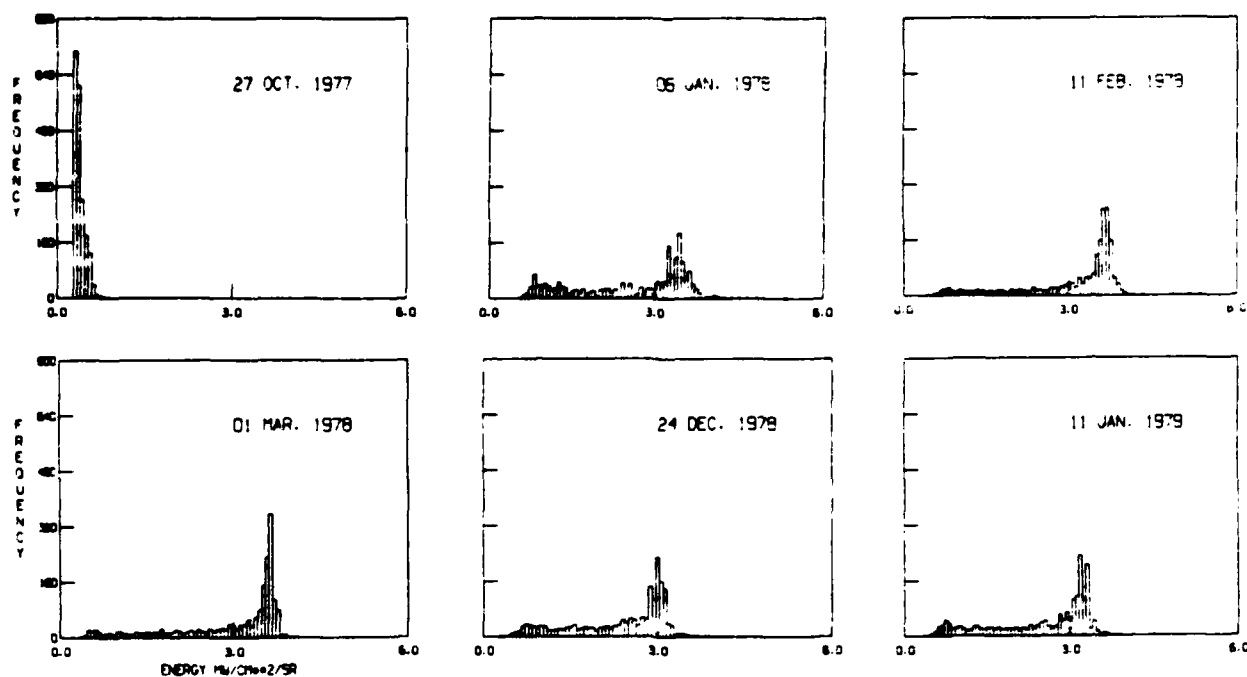
HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED & RESAMPLED  
OPEN AREAS



b. MSS band 7.

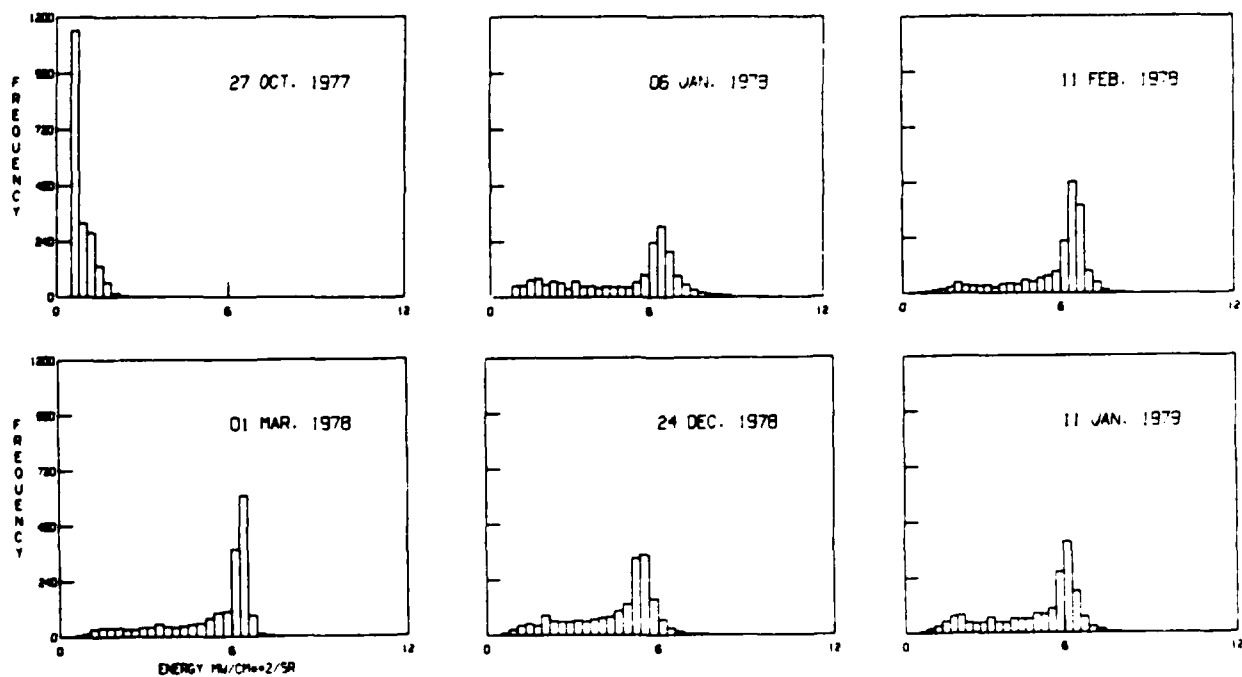
Figure 26. Landsat histograms (corrected and resampled) for the open areas class.

HISTOGRAM: BAND 5  
SOLAR ZENITH CORRECTED & RESAMPLED  
WATER



*a. MSS band 5.*

HISTOGRAM: BAND 7  
SOLAR ZENITH CORRECTED & RESAMPLED  
WATER



*b. MSS band 7.*

Figure 27. Landsat histograms (corrected and resampled) for the water class.

**Table 6. Statistics of MSS band 5 histograms. Data have been converted to radiance values (mW cm<sup>-2</sup>/sr), corrected for sun angle effects, and resampled to equal intervals.**

Statistic	Landsat-2					Landsat-3	
	27 Oct 77	6 Jan 78	11 Feb 78	1 Mar 78	31 May 78	24 Dec 78	11 Jan 79
<b>a. Total area</b>							
$\bar{X}$	0.43	1.01	1.00	0.96	0.35	0.79	0.86
Q2	0.37	0.83	0.77	0.71	0.32	0.63	0.69
Mode	0.35	0.80	0.67	0.60	0.35	0.60	0.60
s	0.14	0.48	0.58	0.62	0.04	0.44	0.47
Q1	0.31	0.72	0.64	0.54	0.30	0.53	0.58
Q3	0.46	1.02	1.06	1.08	0.34	0.80	0.90
P10	0.28	0.65	0.57	0.45	0.28	0.45	0.51
P90	0.56	1.43	1.59	1.63	0.36	1.15	1.26
Skew'	0.63	0.43	0.58	0.57	0.04	0.42	0.55
Skew'	1.45	1.11	1.21	1.19	2.80	1.06	1.11
Skew'	0.23	0.30	0.38	0.35	0.00	0.21	0.31
Skew'	0.37	0.55	0.61	0.55	0.03	0.47	0.52
Skew (Moment)	2.30	3.15	2.71	2.29	1.52	3.08	3.02
Kurtosis'	0.26	0.19	0.20	0.23	0.25	0.19	0.21
Kurtosis (Moment)	11.78	14.72	11.23	8.91	12.80	14.19	13.56
Kurtosis (Mode)	0.32	0.18	0.16	0.12	0.77	0.16	0.17

<b>b. Softwoods</b>							
$\bar{X}$	0.38	0.92	0.89	0.78	0.35	0.77	0.83
Q2	0.32	0.74	0.67	0.53	0.32	0.61	0.65
Mode	0.35	0.73	0.67	0.48	0.35	0.60	0.60
s	0.11	0.49	0.56	0.62	0.04	0.45	0.48
Q1	0.29	0.68	0.60	0.45	0.29	0.53	0.57
Q3	0.37	0.85	0.80	0.71	0.34	0.72	0.78
P10	0.25	0.61	0.55	0.40	0.26	0.46	0.52
P90	0.45	1.21	1.30	1.33	0.36	1.07	1.20
Skew'	0.26	0.38	0.39	0.49	0.00	0.36	0.47
Skew'	1.51	1.08	1.17	1.22	2.40	1.07	1.13
Skew'	0.18	0.28	0.35	0.40	0.00	0.18	0.26
Skew'	0.28	0.58	0.69	0.73	-0.08	0.52	0.61
Skew (Moment)	4.15	3.51	3.31	3.00	1.98	3.22	3.21
Kurtosis'	0.20	0.14	0.13	0.14	0.22	0.16	0.15
Kurtosis (Moment)	30.92	15.84	14.41	12.08	15.68	14.17	13.90
Kurtosis (Mode)	0.49	0.27	0.25	0.24	0.73	0.20	0.23

Explanation:

$$\text{Skew}' = \frac{(\bar{X} - \text{mode})}{s} \quad \text{Skew}' = \frac{3(\bar{X} - Q2)}{s} \quad \text{Skew}' = \frac{Q3 - 2Q2 + Q1}{Q3 - Q1}$$

$$\text{Skew}' = \frac{P90 - 2Q2 + P10}{P90 - P10} \quad \text{Skew (Moment)} = \frac{(\bar{X}_j - \bar{X})^3}{N(s^3)}$$

$$\text{Kurtosis}' = \frac{0.5(Q3 - Q1)}{P90 - P10} \quad \text{Kurtosis (Moment)} = \frac{(\bar{X}_j - \bar{X})^4}{N(s^4)}$$

$$\text{Kurtosis (Mode)} = \frac{\text{Population (mode)}}{\text{Population (total)}}$$

where  $\bar{X}$  = mean,  $s$  = standard deviation,  $Q2$  = median,  $Q1$  = first quartile,  $Q3$  = third quartile,  $P10$  = 10th percentile,  $P90$  = 90th percentile.

Table 6 (cont'd). Statistics of MSS band 5 histograms.

Statistic	Landsat-2					Landsat-3	
	27 Oct 77	6 Jan 78	11 Feb 78	1 Mar 78	31 May 78	24 Dec 78	11 Jan 79
<b>c. Hardwoods</b>							
$\bar{X}$	0.52	1.12	1.15	1.19	0.36	0.81	0.89
Q2	0.47	1.00	1.03	1.08	0.32	0.71	0.78
Mode	0.48	0.99	0.80	0.99	0.35	0.60	0.60
s	0.14	0.35	0.42	0.43	0.04	0.29	0.32
Q1	0.40	0.84	0.80	0.83	0.30	0.56	0.62
Q3	0.56	1.24	1.34	1.40	0.34	0.93	1.01
P10	0.34	0.73	0.67	0.67	0.29	0.48	0.54
P90	0.66	1.57	1.71	1.74	0.36	1.18	1.27
Skew <sup>1</sup>	0.33	0.37	0.85	0.47	0.15	0.69	0.89
Skew <sup>2</sup>	1.08	1.03	0.90	0.77	2.88	1.04	1.02
Skew <sup>3</sup>	0.05	0.21	0.15	0.14	0.00	0.23	0.18
Skew <sup>4</sup>	0.16	0.38	0.32	0.24	0.16	0.35	0.34
Skew (Moment)	1.37	1.64	1.17	0.91	9.63	1.36	1.51
Kurtosis <sup>1</sup>	0.25	0.24	0.26	0.27	0.26	0.26	0.27
Kurtosis (Moment)	7.28	9.79	4.82	3.98	11.91	6.35	7.80
Kurtosis (Mode)	0.22	0.12	0.09	0.08	0.81	0.12	0.12
<b>d. Mixed forest</b>							
$\bar{X}$	0.43	0.94	0.92	0.87	0.35	0.72	0.80
Q2	0.37	0.81	0.75	0.68	0.32	0.62	0.67
Mode	0.35	0.80	0.67	0.60	0.35	0.60	0.60
s	0.13	0.35	0.43	0.48	0.03	0.31	0.35
Q1	0.32	0.72	0.64	0.54	0.30	0.51	0.57
Q3	0.44	0.97	0.97	0.96	0.34	0.76	0.85
P10	0.29	0.65	0.57	0.46	0.28	0.44	0.50
P90	0.54	1.21	1.35	1.42	0.35	1.01	1.13
Skew <sup>1</sup>	0.61	0.41	0.58	0.56	0.01	0.38	0.57
Skew <sup>2</sup>	1.43	1.08	1.16	1.19	3.06	1.02	1.09
Skew <sup>3</sup>	0.19	0.26	0.31	0.33	0.00	0.17	0.25
Skew <sup>4</sup>	0.36	0.41	0.52	0.53	-0.03	0.37	0.44
Skew (Moment)	2.61	3.39	2.80	2.39	0.55	2.93	2.98
Kurtosis <sup>1</sup>	0.25	0.22	0.22	0.22	0.27	0.21	0.22
Kurtosis (Moment)	13.70	19.10	13.34	10.26	6.56	15.84	15.44
Kurtosis (Mode)	0.03	0.20	0.17	0.15	0.78	0.16	0.18
<b>e. Open areas</b>							
$\bar{X}$	0.46	2.25	3.80	3.85	0.47	1.92	2.11
Q2	0.42	2.24	2.40	2.48	0.45	1.97	2.22
Mode	0.41	3.41	3.54	3.54	0.48	2.84	3.16
s	0.10	0.86	1.71	1.69	0.07	0.77	0.84
Q1	0.35	1.41	1.71	1.86	0.40	1.20	1.35
Q3	0.51	3.05	2.86	2.91	0.51	2.52	2.85
P10	0.30	1.00	1.13	1.09	0.37	0.78	0.80
P90	0.57	3.33	3.04	3.16	0.58	2.84	3.11
Skew <sup>1</sup>	0.49	-1.34	0.16	0.18	-0.15	-1.20	-1.25
Skew <sup>2</sup>	1.17	0.03	2.47	2.43	0.55	-0.19	-0.39
Skew <sup>3</sup>	0.09	-0.02	-0.20	-0.19	0.09	-0.16	-0.16
Skew <sup>4</sup>	0.09	-0.07	-0.33	-0.35	0.18	-0.16	-0.23
Skew (Moment)	0.19	-0.17	-1.26	-1.29	1.10	-0.25	-0.30
Kurtosis <sup>1</sup>	0.28	0.35	0.30	0.25	0.27	0.32	0.33
Kurtosis (Moment)	2.30	1.69	1.76	1.88	3.20	1.77	1.79
Kurtosis (Mode)	0.24	0.06	0.08	0.10	0.33	0.06	0.06

**Table 6 (cont'd). Statistics of MSS band 5 histograms. Data have been converted to radiance values (mW cm<sup>-2</sup>/sr), corrected for sun angle effects, and resampled to equal intervals.**

Statistic	Landsat-2					Landsat-3	
	27 Oct 77	6 Jan 78	11 Feb 78	1 Mar 78	31 May 78	24 Dec 78	11 Jan 79
<i>f. Water</i>							
$\bar{X}$	0.37	2.57	3.07	2.92	0.35	2.33	2.46
Q2	0.31	3.03	3.45	3.38	0.31	2.66	2.83
Mode	0.29	3.41	3.67	3.60	0.35	2.97	3.16
<i>s</i>	0.09	1.02	0.87	0.93	0.06	0.81	0.89
Q1	0.27	1.55	2.74	2.46	0.28	1.70	1.76
Q3	0.38	3.37	3.61	3.55	0.34	2.94	3.13
P10	0.24	0.92	1.52	1.27	0.25	0.92	0.91
P90	0.47	3.54	3.70	3.61	0.39	3.05	3.25
Skew'	0.92	-0.33	-0.69	-0.73	0.03	-0.78	-0.78
Skew <sup>2</sup>	1.80	-1.38	-1.32	-1.48	1.90	-1.22	-1.24
Skew <sup>3</sup>	0.18	-0.63	-0.63	-0.69	-0.02	-0.55	-0.56
Skew <sup>4</sup>	0.36	-0.61	-0.77	-0.81	0.08	-0.64	-0.64
Skew (Moment)	1.26	-0.56	-1.40	-1.29	1.83	-0.83	-0.82
Kurtosis'	0.25	0.35	0.20	0.23	0.20	0.29	0.29
Kurtosis (Moment)	4.52	1.86	3.91	3.42	8.88	2.36	2.30
Kurtosis (Mode)	0.36	0.10	0.13	0.18	0.55	0.12	0.12

**Table 7. Statistics of MSS band 7 histograms. Data have been converted to radiance values (mW cm<sup>-2</sup>/sr), corrected for sun angle effects, and resampled to equal intervals.**

Statistic	Landsat-2					Landsat-3	
	27 Oct 77	6 Jan 78	11 Feb 78	1 Mar 78	31 May 78	24 Dec 78	11 Jan 79
<i>a. Total area</i>							
$\bar{X}$	1.24	2.29	2.32	2.30	1.90	1.88	2.07
Q2	1.06	1.80	1.89	1.85	1.72	1.59	1.71
Mode	1.10	1.67	1.96	1.67	1.67	1.67	1.67
<i>s</i>	0.40	1.07	1.08	1.07	0.52	0.86	0.95
Q1	0.83	1.40	1.50	1.45	1.37	1.22	1.36
Q3	1.34	2.41	2.50	2.57	2.14	1.96	2.20
P10	0.59	1.05	1.19	1.16	1.14	0.90	1.10
P90	1.62	3.30	3.51	3.52	2.48	2.72	3.02
Skew'	0.35	0.49	0.33	0.58	0.44	0.25	0.42
Skew <sup>2</sup>	1.33	1.11	1.19	1.25	1.05	1.03	1.16
Skew <sup>3</sup>	0.09	0.20	0.21	0.28	0.10	0.01	0.18
Skew <sup>4</sup>	0.08	0.33	0.39	0.42	0.14	0.25	0.37
Skew (Moment)	0.60	1.91	1.84	1.65	0.09	1.93	2.03
Kurtosis'	0.25	0.22	0.21	0.24	0.29	0.20	0.22
Kurtosis (Moment)	3.88	8.05	7.14	6.12	2.73	8.33	8.39
Kurtosis (Mode)	0.31	0.19	0.20	0.20	0.21	0.21	0.22

Explanation:

$$\text{Skew}' = \frac{(\bar{X} - \text{mode})}{s} \quad \text{Skew}' = \frac{3(\bar{X} - Q2)}{s} \quad \text{Skew}' = \frac{Q3 - 2Q2 + Q1}{Q3 - Q1}$$

$$\text{Skew}' = \frac{P90 - 2Q2 + P10}{P90 - P10} \quad \text{Skew (Moment)} = \frac{(\bar{X}_j - \bar{X})'}{N(s')^3}$$

$$\text{Kurtosis}' = \frac{0.5(Q3 - Q1)}{P90 - P10} \quad \text{Kurtosis (Moment)} = \frac{(\bar{X}_j - \bar{X})'}{N(s')^4}$$

$$\text{Kurtosis (Mode)} = \frac{\text{Population (mode)}}{\text{Population (total)}}$$

where  $\bar{X}$  = mean,  $s$  = standard deviation, Q2 = median, Q1 = first quartile, Q3 = third quartile, P10 = 10th percentile, P90 = 90th percentile.



Table 7 (cont'd). Statistics of MSS band 7 histograms.

Statistic	Landsat-2					Landsat-3	
	27 Oct 77	6 Jan 78	11 Feb 78	1 Mar 78	31 May 78	24 Dec 78	11 Jan 79
<b>b. Softwoods</b>							
$\bar{X}$	1.04	1.94	2.00	1.88	1.32	1.77	1.93
$Q_2$	0.90	1.57	1.61	1.44	1.19	1.46	1.93
Mode	1.10	1.67	1.67	1.39	1.39	1.67	1.67
$s$	0.31	0.98	1.00	1.03	0.16	0.83	0.92
$Q_1$	0.68	1.31	1.34	1.19	1.07	1.18	1.30
$Q_3$	1.07	1.91	1.94	1.82	1.30	1.78	1.89
$P_{10}$	0.53	1.07	1.13	0.97	0.91	0.92	1.11
$P_{90}$	1.29	2.65	2.81	2.83	1.37	2.36	2.69
Skew <sup>1</sup>	-0.17	0.27	0.33	0.48	-0.41	0.12	0.28
Skew <sup>2</sup>	1.42	1.15	1.19	1.29	2.32	1.11	1.21
Skew <sup>3</sup>	-0.11	0.14	0.11	0.20	-0.08	0.06	0.12
Skew <sup>4</sup>	0.03	0.37	0.43	0.49	-0.25	0.25	0.43
Skew (Moment)	1.12	2.82	2.68	2.53	-0.23	2.52	2.60
Kurtosis <sup>1</sup>	0.26	0.19	0.18	0.17	0.26	0.21	0.19
Kurtosis (Moment)	7.57	12.44	11.22	9.82	3.66	10.83	10.73
Kurtosis (Mode)	0.42	0.31	0.28	0.29	0.66	0.27	0.30
<b>c. Hardwoods</b>							
$\bar{X}$	1.52	2.52	2.68	2.78	2.70	1.99	2.20
$Q_2$	1.38	2.21	2.39	2.55	2.53	1.77	1.91
Mode	1.67	1.96	1.96	2.82	2.53	1.96	1.96
$s$	0.42	1.04	0.94	0.85	0.21	0.75	0.82
$Q_1$	1.08	1.59	1.85	2.00	2.38	1.32	1.46
$Q_3$	1.65	3.01	3.09	3.17	2.72	2.27	2.55
$P_{10}$	0.83	1.17	1.45	1.61	2.29	0.93	1.13
$P_{90}$	1.91	3.79	3.83	3.78	2.86	2.91	3.17
Skew <sup>1</sup>	-0.37	0.53	0.76	-0.05	0.77	0.04	0.29
Skew <sup>2</sup>	0.95	0.88	0.92	0.79	2.43	0.89	1.05
Skew <sup>3</sup>	-0.08	0.13	0.12	0.06	0.13	0.05	0.17
Skew <sup>4</sup>	-0.02	0.21	0.21	0.14	0.17	0.16	0.23
Skew (Moment)	0.10	0.87	0.74	0.58	0.46	0.75	0.89
Kurtosis <sup>1</sup>	0.27	0.27	0.26	0.27	0.30	0.24	0.27
Kurtosis (Moment)	2.96	4.62	3.61	3.29	2.76	4.20	4.47
Kurtosis (Mode)	0.27	0.12	0.14	0.14	0.48	0.19	0.17
<b>d. Mixed forest</b>							
$\bar{X}$	1.24	2.06	2.19	2.18	1.91	1.79	1.98
$Q_2$	1.08	1.83	1.88	1.81	1.75	1.57	1.69
Mode	1.10	1.67	1.96	1.67	1.67	1.67	1.67
$s$	0.37	0.88	0.87	0.88	0.31	0.70	0.78
$Q_1$	0.85	1.42	1.50	1.47	1.52	1.20	1.35
$Q_3$	1.32	2.36	2.37	2.38	2.01	1.92	2.12
$P_{10}$	0.62	1.00	1.18	1.19	1.39	0.88	1.06
$P_{90}$	1.57	3.10	3.09	3.16	2.19	2.44	2.77
Skew <sup>1</sup>	0.39	0.44	0.27	0.58	0.78	0.17	0.39
Skew <sup>2</sup>	1.33	0.79	1.09	1.24	1.56	0.94	1.08
Skew <sup>3</sup>	0.05	0.13	0.14	0.24	0.05	-0.03	0.11
Skew <sup>4</sup>	0.04	0.21	0.27	0.37	0.10	0.12	0.26
Skew (Moment)	0.62	1.79	1.72	1.68	0.15	1.57	1.75
Kurtosis <sup>1</sup>	0.25	0.22	0.23	0.23	0.30	0.28	0.23
Kurtosis (Moment)	4.42	8.53	7.83	6.98	2.26	7.96	8.16
Kurtosis (Mode)	0.32	0.18	0.22	0.22	0.32	0.22	0.22

**Table 7 (cont'd). Statistics of MSS band 7 histograms. Data have been converted to radiance values ( $\text{mW cm}^{-2}/\text{sr}$ ), corrected for sun angle effects, and resampled to equal intervals.**

Statistic	Landsat-2					Landsat-3	
	27 Oct 77	6 Jan 78	11 Feb 78	1 Mar 78	31 May 78	24 Dec 78	11 Jan 79
<b>e. Open areas</b>							
$\bar{X}$	1.23	4.40	4.72	4.79	1.96	3.69	4.22
Q2	1.07	4.39	4.85	4.89	1.82	3.69	4.35
Mode	1.10	5.98	6.27	6.27	1.96	5.41	5.98
s	0.46	1.59	1.39	1.36	0.16	1.30	1.50
Q1	0.77	2.96	3.57	3.77	1.72	2.40	2.82
Q3	1.41	5.70	5.76	5.83	1.91	4.68	5.43
P10	0.43	1.98	2.54	2.60	1.59	1.67	1.89
P90	1.66	6.14	5.23	6.16	2.04	5.18	5.85
Skew <sup>1</sup>	0.29	-0.99	-1.11	-1.09	0.00	-1.32	-1.18
Skew <sup>2</sup>	1.05	0.02	-0.28	-0.22	2.66	-0.00	-0.25
Skew <sup>3</sup>	0.06	-0.04	-0.17	-0.09	0.00	-0.13	-0.17
Skew <sup>4</sup>	-0.04	-0.16	-0.25	-0.28	-0.01	-0.15	-0.24
Skew (Moment)	0.25	-0.25	-0.55	-0.74	0.26	-0.29	-0.40
Kurtosis <sup>1</sup>	0.26	0.33	0.30	0.29	0.22	0.32	0.33
Kurtosis (Moment)	2.61	2.01	2.38	2.75	5.89	1.90	1.97
Kurtosis (Mode)	0.26	0.11	0.10	0.16	0.72	0.10	0.11
<b>f. Water</b>							
$\bar{X}$	0.76	4.84	5.52	5.16	0.63	4.30	4.72
Q2	0.48	5.65	6.01	5.78	0.45	4.79	5.36
Mode	0.52	6.27	6.27	6.27	0.52	5.41	5.98
s	0.34	2.03	1.47	1.54	0.17	1.45	1.68
Q1	0.36	2.90	4.89	4.35	0.34	3.14	3.33
Q3	0.81	6.21	6.31	6.08	0.60	5.23	5.85
P10	0.29	1.47	2.80	2.32	0.28	1.79	1.74
P90	1.14	6.66	6.53	6.22	0.76	5.55	6.15
Skew <sup>1</sup>	0.69	-0.71	-0.51	-0.72	0.64	-0.76	-0.75
Skew <sup>2</sup>	2.45	-1.21	-1.00	-1.20	3.22	-1.00	-1.14
Skew <sup>3</sup>	0.46	-0.67	-0.58	-0.65	0.18	-0.58	-0.62
Skew <sup>4</sup>	0.54	-0.61	-0.72	-0.77	0.30	-0.59	-0.64
Skew (Moment)	1.43	-0.54	-1.42	-1.33	1.39	-0.82	-0.80
Kurtosis <sup>1</sup>	0.27	0.32	0.19	0.22	0.27	0.28	0.29
Kurtosis (Moment)	4.47	2.08	4.13	3.56	4.30	2.59	2.40
Kurtosis (Mode)	0.59	0.16	0.25	0.31	0.68	0.18	0.20

**Table 8. Average snow depth (cm) for each land cover class and total area.**

Land cover class	6 Jan 78	11 Feb 78	1 Mar 78	24 Dec 78	11 Jan 79
Softwoods	38.1	66.0	63.5	45.7	50.8
Hardwoods	43.2	72.4	69.8	61.0	62.2
Mixed forest	44.4	77.5	76.2	54.6	63.5
Open areas	47.0	76.2	73.7	61.0	64.8
Total area	43.2	74.9	71.1	54.6	55.9

levels. For the total area histograms the means vary by less than  $0.05 \text{ mW cm}^{-2} \text{ sr}^{-1}$  for the three Landsat-2 scenes and by 0.44 for all snow days (Fig. 24). Changes in skewness and kurtosis are irregular and do not relate well with increasing snow depth.

In MSS 5 the measures of central tendency and percentiles are often within  $0.064 \text{ mW cm}^{-2} \text{ sr}^{-1}$  between days, particularly when those of one satellite's observations are considered. Where differences are greater than 0.064, most commonly they show decreases in magnitude for the days with greater snow depth. The greater contribution of snow to the observed Landsat signal is not occurring with increasing snow depth because of the dominance of the forest canopy within the sensor's instantaneous field of view.

Within the nonforested cover classes, the corrected histograms show a relationship between increasing snow depth and the magnitude of reflected energy. As the snow accumulates throughout the snow season, the means and in particular the first quartile and 10th percentile increase in magnitude. The moment coefficients of skewness and kurtosis for the open areas and frozen water surfaces also show a consistent change in histogram shape as the snow depth increases. Snow depth measurements were not made over the water surfaces, but the lakes and rivers remained frozen throughout the winter season. Even with differences in accumulation caused by drifting, it may be assumed that as regional snow depth increased, the accumulation on the frozen water surfaces also increased.

In MSS 7, the water surfaces show consistent increases in magnitude (within each Landsat group) for the mean and particularly the first quartile and 10th percentile. These indicate a reduction in the low reflecting portions of the histogram. This is also shown in moment coefficients of skewness and kurtosis, both of which are dimensionless indices of data distribution. Thus, they allow for comparison between the two Landsat passes. The moment coefficient of skewness is negative because of the high mean values and the departure from symmetry to the left. It increases with snow depth largely because of the increasing value of the mean. The moment coefficient of kurtosis will increase as a distribution becomes more peaked. A normal distribution will have a kurtosis (moment) of 3. Thus, the water histograms show increasing kurtosis with snow depth.

For open areas, the histograms again show in both bands an increase in magnitude, skewness,

and kurtosis. The trends in the skewness and kurtosis are less useful for open areas than for water areas because of the strong divergence from a Gaussian distribution for the open areas.

Although the differences between the snow scenes are variable in their suggestion of a snow depth/regional histogram relationship, this is not the case for comparing the snow scenes, considered as a group, with the non-snow scenes. The most striking differences occur for the water surfaces in MSS 5 and 7. Increases of greater than 500% are found for all measures of central tendency, quartiles, and percentiles. The water histograms under non-snow conditions display low radiance values with a tight cluster around the mean (Fig. 27). Subsequent freezing and covering by snow increases the histogram mode to higher energy values with a larger standard deviation. This is described by the change in magnitude of the mean, median, etc., the large increase in standard deviation, the reversal of skewness from positive to negative, and the decreased value of the moment coefficient of kurtosis.

Open areas are affected similarly to water by the addition of snow cover. The snow depths in all snow scenes are greater than 38 cm. Most low-lying vegetation is covered, providing a largely undisturbed, highly reflective snowpack. The percentage changes in MSS 7 are not as great as for water for two reasons: 1) irregularities in the vegetation canopy and possible anthropogenic structures in the agriculture areas contribute sections of lower reflectance, and 2) the non-snow reflectance of the open lands is higher than that of water. This is particularly true for the May scene when vegetation growth results in a higher near-infrared reflectance. Water absorbs radiation in the near-infrared wavelengths. Percentage changes for the measures in MSS 5 are similar to those for water. The absolute dimension of the snow values is not as high as for water in winter. Again, this is because of the presence of darker surfaces of dormant vegetation.

For forested sites, the contrast between snow and no-snow scenes will depend on species composition, season of the no-snow scene, and band wavelength. The softwood trees retain their leaves throughout the winter and display a high crown closure. In MSS 5, the histograms are almost identical for the October and May scenes. Increases of close to 100% are shown in these forests with the addition of snow. Radiance changes in MSS 7 are less pronounced, although they still occur. This is largely because of the infrared reflectance of the

conifer leaf structure, which remains the same throughout the autumn and winter.

The results of snow cover in the hardwoods and mixed forest are similar to the softwoods. In all seasons, the hardwoods display energy values several levels higher than do the evergreens in both MSS 5 and 7. Canopy structure and the loss of leaves in the winter are responsible for this increased reflectance. Percentage changes between no-snow and snow scenes are comparable for all forest types. The one exception occurs when the May scene and the winter scenes for MSS 7 are compared. In northern Maine, the hardwoods leaf out in late May. The leaf cellular structure and geometry result in high infrared reflectance. The magnitude of the energy in MSS 7 during May is equal to and often exceeds that for the snow-covered scene.

The forests display a smaller change between non-snow and snow conditions than either open areas or water. However, there is still a measurable, predictable displacement by several histogram levels for most statistical measures.

If Landsat bands 5 and 7 are considered together, the Landsat histograms—corrected to account for the solar angle and sensor calibration—could provide an automated evaluation of the presence and areal distribution of a snowpack, even in a heavily forested region such as northern New England. The MSS 7 statistics for the 27 Oct scene are significantly different from the other scenes (Table 7). Because of leaf emergence, the 31 May MSS 7 histogram statistics are similar to the snow scenes, although this similarity does not appear in MSS band 5.

#### **Landsat data as input to the SSARR model**

The 31 May Landsat land cover classification provided a basis upon which the point measurements of water equivalent could be used in the SSARR model. The snow course measurements were selected to provide data for the various land cover classes present in the entire hydrologic basin. The ground measurements of water equivalent of snow were subsequently area-weighted to the May Landsat classification to derive mean regional water equivalent estimates for each of the five Landsat winter scenes (Table 9).

The 1 Mar 78 estimate of 19.46 cm of water equivalent was used as an input value to the SSARR model. This value was an estimate of snow water equivalent before the spring melt period had occurred. The time period of 1 March

**Table 9. Areal determination of snow depth and water equivalent for the basin.**

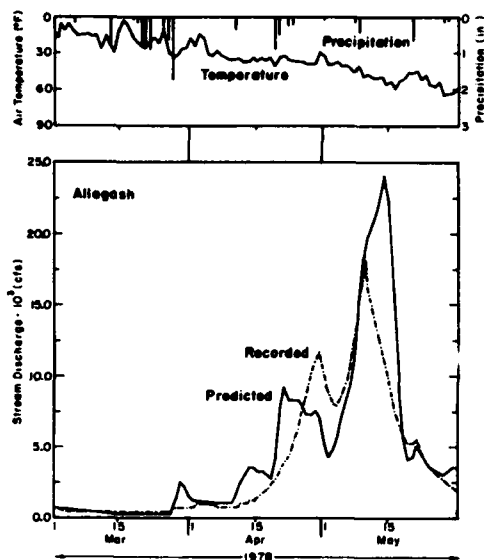
<i>Landsat date</i>	<i>Snow depth (cm)</i>	<i>Water equivalent (cm)</i>
6 Jan 78	42.27	7.42
11 Feb 78	73.58	20.24
1 Mar 78	70.94	19.46
24 Dec 78	51.92	6.10
11 Jan 79	58.95	14.30

through 31 May 1978 was used for the simulation model run. Calibration of the Upper Saint John River Basin was accomplished by the New Brunswick Flood Forecast Centre. The parameters of soil moisture index and rain-freeze temperature were adjusted to optimize the prediction of runoff. The results of the SSARR run are shown in Figure 28.

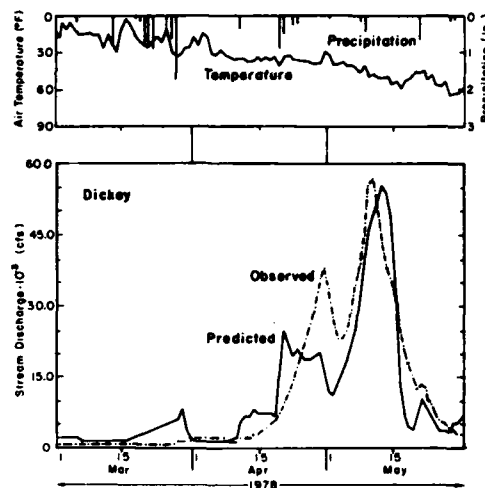
The initial SSARR run showed that the magnitude of the first predicted runoff peak compared to the observed values for the Ninemile Bridge, Dickey, and Allagash subbasins was 58%, 70%, and 78%, respectively. The magnitude of the second predicted runoff peak for the Dickey and Allagash subbasins was 97% and 70%, respectively, of the recorded stream discharge values, whereas the second runoff peak for the Ninemile Bridge subbasin was overpredicted by 3%.

The time of the first predicted peak of runoff was earlier by 8 days for the Ninemile Bridge and Allagash subbasins and by 9 days for the Dickey subbasin. The timing of the second predicted peak improved for Ninemile Bridge, Dickey, and Allagash, with a delay of 2, 3, and 5 days, respectively.

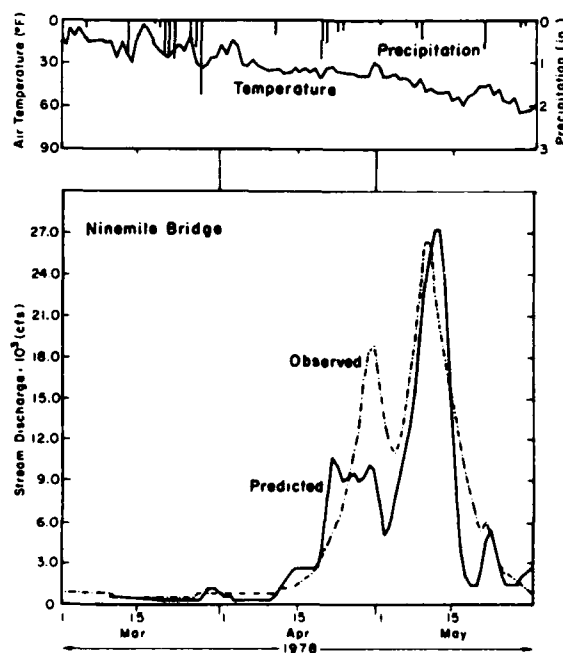
In summary, the initial baseflow period (1-27 March) predicted by the SSARR model was within 78% of the recorded stream discharge values. The spring melt recession (10-31 May 1978) predicted by the SSARR model was within 67% of the recorded stream discharge values. The timing of the six runoff peaks (Fig. 28) lagged by 2 to 9 days. The magnitude of the six predicted runoff peaks was within 75% of the recorded streamflow measurements. The error in the prediction of the initial storm peak for all three subbasins was attributed to the underprediction of snowmelt by the SSARR model caused by a rain-on-snow event that occurred on 28 March.



*a. Allagash subbasin.*



*b. Dickey subbasin.*



*c. Ninemile Bridge subbasin.*

*Figure 28. SSAR model run for the 1 March to 31 May 1978 time period.*

In temperate continental climatic zones, additional complications in spring melt arise when rain-on-snow events occur. The rainfall coupled with above-freezing temperatures can cause the snowpack to melt very rapidly. This type of occurrence may have to be modeled as a separate subroutine with SSARR. Additional work on recalibrating the basin peak timing and melt rate factors is also required.

## CONCLUSIONS

Initial histogram analysis presented in this study indicated that a good correlation existed between the satellite radiometric measurements and mean snow depth in the 420-km<sup>2</sup> area. Using Landsat uncorrected data an equation was developed to predict snow depth with a standard error of estimate of  $\pm 5$  cm.

However, when subsequent corrections for sensor calibrations and solar elevation were taken into consideration, this correlation was eliminated for forested land cover. For open clearings and frozen water surfaces, definite increases in histogram means, quartiles, percentiles, kurtosis, and skewness were observed as regional snow depth increased. Some of our correlations would compare better with western snowpack satellite relationships if the models for western snowpacks had to contend with freeze-thaw cycles and rain-on-snow events. These two factors will definitely change the reflectance and brightness characteristics of the snowpack.

The ground measurements of water equivalent were area-weighted by the May land cover classification to derive a mean regional water equivalent estimate for input to the SSARR model. For the time period of 1 March through 31 May 1978, the SSARR model prediction was within 78% of the measured runoff for the initial baseflow period and within 67% for the spring melt recession period. The timing and magnitude of the runoff peaks requires additional work on recalibrating the basin peak timing factors and melt rate factors.

A technique was developed for using minimal ground truth snow course measurements coupled with a Landsat land cover classification to derive a mean areal average of water equivalent. This technique could be demonstrated for other watersheds by selecting an appropriate number of snow courses representative of land cover types. In forested basins where land cover can change within a few

years' time, the Landsat data can be used periodically to develop a current land cover inventory of the basin.

## LITERATURE CITED

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# APPENDIX A: SNOW DEPTH AND WATER EQUIVALENT DATA

Table A1. Snow property data for Allagash, 1977-78.

Date	Site 1		Site 3		Site 4		Site 5		Site 7		Site 9		Site 10		Site 11		Site 12		Site 13		Site 15	
	Depth (cm)	Dens (g/cm <sup>3</sup> )	Depth (cm)	Dens (g/cm <sup>3</sup> )	Depth (cm)	Dens (g/cm <sup>3</sup> )	Depth (cm)	Dens (g/cm <sup>3</sup> )	Depth (cm)	Dens (g/cm <sup>3</sup> )	Depth (cm)	Dens (g/cm <sup>3</sup> )	Depth (cm)	Dens (g/cm <sup>3</sup> )	Depth (cm)	Dens (g/cm <sup>3</sup> )	Depth (cm)	Dens (g/cm <sup>3</sup> )	Depth (cm)	Dens (g/cm <sup>3</sup> )	Depth (cm)	Dens (g/cm <sup>3</sup> )
12/20/77- 12/21/77 Snow pit	40.1	0.152	40.4	0.151	29.7	0.104	43.7	0.181	41.6	0.171	46.2	0.181									96.6	0.141
		0.194										0.181										
1/7/78- 1/8/78 Snow pit	45.7	0.162	59.9	0.178	29.2	0.130	45.0	0.120	59.9	0.155	50.8	0.159	46.5	0.206	44.5	0.191	45.7	0.161	46.0	0.166	42.7	0.149
		0.178										0.198										0.202
1/25/78- 1/26/78 Snow pit	76.2	0.206	65.5	0.220	50.8	0.125	64.0	0.125	75.7	0.226	75.7	0.195	69.1	0.250	65.5	0.275	67.8	0.270	66.1	0.268	66.1	0.190
		0.185										0.235										0.224
2/12/78- 2/13/78 Snow pit	71.5	0.281	69.8	0.248	55.4	0.193	83.0	0.259	74.2	0.287	72.4	0.288	75.7	0.295	70.4	0.314	74.2	0.308	77.0	0.317	75.4	0.249
		0.226										0.259										0.232
3/2/78- 3/3/78 Snow pit	74.4	0.293	67.8	0.256	51.6	0.221	80.8	0.256	72.9	0.300	69.8	0.277	74.2	0.274	64.5	0.271	71.6	0.284	75.4	0.315	74.2	0.250
		0.306										0.320										0.257
3/20/78- 3/21/78 Snow pit	86.4	0.336	82.0	0.304	67.5	0.255	91.4	0.335	90.2	0.310	79.5	0.332	90.2	0.307	83.8	0.336	90.2	0.329	86.4	0.332	85.6	0.287
		0.279										0.305										0.328
4/1/78- 4/8/78 Snow pit	111.8	0.309	94.5	0.309	78.0	0.234	106.7	0.336	100.5	0.336	99.6	0.331	102.4	0.315	95.2	0.360	102.1	0.328	100.8	0.322	98.3	0.305
		0.326										0.366										0.355
4/12/78- 4/15/78 Snow pit	97.0	0.319	84.6	0.300	71.9	0.235	92.2	0.325	101.1	0.308	90.9	0.363	91.9	0.295	86.4	0.344	93.5	0.321	87.6	0.320	85.6	0.318
		0.366										0.426										0.362
4/19/78- 4/20/78 Snow pit	74.9	0.329	72.9	0.296	65.5	0.221	88.4	0.307	85.1	0.319	78.0	0.332	80.5	0.322	82.0	0.316	80.8	0.308	79.2	0.275	75.1	0.306
		0.480										0.444										0.408
4/26/78- 4/27/78 Snow pit	51.5	0.294	48.5	0.292	41.9	0.200	64.0	0.298	65.5	0.285	40.1	0.266	60.2	0.255	49.5	0.298	56.6	0.269	52.8	0.207	44.4	0.297
		0.490										0.471										0.480
5/1/78- Snow pit	No snow		55.0	0.304	51.0	0.180																0.296
																						0.340

-----Site 13 inaccessible due to muddy roads

Table A2. Snow property data for Allagash, 1978-79 data.

Date	Site 1		Site 3		Site 4		Site 5		Site 7		Site 9		Site 10		Site 11		Site 12		Site 13	
	Depth (cm)	Den (g/cm <sup>3</sup> )	Depth (cm)	Den (g/cm <sup>3</sup> )	Depth (cm)	Den (g/cm <sup>3</sup> )	Depth (cm)	Den (g/cm <sup>3</sup> )	Depth (cm)	Den (g/cm <sup>3</sup> )	Depth (cm)	Den (g/cm <sup>3</sup> )	Depth (cm)	Den (g/cm <sup>3</sup> )	Depth (cm)	Den (g/cm <sup>3</sup> )	Depth (cm)	Den (g/cm <sup>3</sup> )	Depth (cm)	Den (g/cm <sup>3</sup> )
12/6/78 Snow pit	28.9	4.6 0.198	24.1	4.3 0.179	18.5	2.5 0.137	35.0	4.6 0.131	35.0	4.8 0.138	33.0	3.0 0.092	19.6	3.6 0.181	19.3	2.8 0.145	11.2	1.8 0.159	19.0	82.8 0.147 0.164
12/15/78 Snow pit																			35.5	3.8 0.114
12/24/78 Snow pit	61.5	8.1 0.152											55.1	7.4 0.134	59.7	8.1 0.136	45.2	5.8 0.084	60.4	7.6 0.125 0.192
1/11/79 Snow pit	64.5	15.1 0.245	57.9	14.7 0.294	45.7	12.7 0.291	67.8	16.0 0.236	62.2	13.5 0.216	65.5	16.0 0.245 0.202								
1/20/79 Snow pit	71.1	--											74.4	17.5 0.245	72.4	19.6 0.270	55.1	10.2 0.184	69.1	16.5 0.239 0.231
1/24/79 Snow pit	72.4	20.1 0.277	59.2	15.2 0.225	56.4	17.5 0.296	66.8	17.8 0.266	65.5	17.8 0.271	72.9	21.6 0.296 0.381								
2/1/79 Snow pit	81.8	22.9 0.279											93.2	23.6 0.255	85.1	23.6 0.277	58.9	13.7 0.232	90.2	22.5 0.248 0.230
2/16/79 Snow pit	74.9	23.8 0.315	69.5	21.1 0.304	56.4	19.1 0.358	76.7	25.9 0.358	69.5	22.1 0.319	74.2	23.4 0.315 0.255								
2/25/79 Snow pit	77.0	20.5 0.284											81.5	25.9 0.319	83.5	24.9 0.299	61.5	14.7 0.239	85.1	25.4 0.298 0.230
3/6/79 Snow pit			62.2	17.8 0.286	50.5	19.6 0.389	72.4	21.6 0.298	66.8	18.5 0.274	66.5	19.6 0.282 0.294								
3/15/79 Snow pit	67.8	17.0 0.251											68.1	22.9 0.336	64.3	24.6 0.385	46.2	14.0 0.302	70.6	22.9 0.324 0.319
3/28/79 Snow pit	55.5	21.1 0.395	41.9	16.0 0.382	41.1	14.7 0.358	55.5	21.1 0.395	51.6	16.5 0.320	42.4	18.5 0.437 0.336								
4/2/79 Snow pit	74.1	1.6 3.16																		
4/11/79 Snow pit	67.5	17.0 0.255											72.9	11.9 0.428	77.2	10.7 0.392	14.7	5.6 0.380	33.5	12.2 0.364 0.380
4/20/79 Snow pit	50.5	13.7 0.455																		
		0.436											17.5	8.9 0.514	26.7	12.2 0.457	13.5	6.9 0.511	22.5	10.7 0.478 0.456

Table A3. Snow property data for Allagash, 1979-80 data.

Date	Site 1		Site 3		Site 4		Site 5		Site 7		Site 9		Site 10		Site 11		Site 12		Site 13		Site 15	
	Depth (cm)	WE (g/cm <sup>3</sup> )	Depth (cm)	WE (g/cm <sup>3</sup> )	Depth (cm)	WE (g/cm <sup>3</sup> )	Depth (cm)	WE (g/cm <sup>3</sup> )	Depth (cm)	WE (g/cm <sup>3</sup> )	Depth (cm)	WE (g/cm <sup>3</sup> )	Depth (cm)	WE (g/cm <sup>3</sup> )	Depth (cm)	WE (g/cm <sup>3</sup> )	Depth (cm)	WE (g/cm <sup>3</sup> )	Depth (cm)	WE (g/cm <sup>3</sup> )	Depth (cm)	WE (g/cm <sup>3</sup> )
12/13/79- 12/21/79 Snow pit	16.0	2.3 0.164	12.7	1.0 0.080	9.6	0.2 0.021	18.5	2.5 0.137	18.1	2.5 0.138	21.0	2.5 0.120	19.0	2.5 0.133	18.5	2.3 0.123	9.4	0.0 --	19.8	2.3 0.115	17.0	2.5 0.169
		0.140										0.128								0.144		
1/6/80- 1/7/80 Snow pit	26.2	3.8 0.146	26.2	4.6 0.175	20.8	4.8 0.231	37.3	7.1 0.190	40.6	6.4 0.156	30.0	4.8 0.161	36.5	7.1 0.196	34.5	5.8 0.170	18.3	3.3 0.181	41.9	8.6 0.206	42.7	8.1 0.190
		0.129										0.192								0.127		
1/14/80- 1/23/80 Snow pit	38.9	6.0 0.170	41.4	6.4 0.155	31.0	5.6 0.180	51.3	9.6 0.188	50.3	9.6 0.192	48.3	9.4 0.195	50.0	9.9 0.198	46.5	8.9 0.191	30.0	4.6 0.152	56.6	12.9 0.229	46.2	9.6 0.209
		0.162										0.181								0.234		
2/11/80- 2/12/80 Snow pit	32.5	5.6 0.112	38.6	7.4 0.191	27.4	3.8 0.139	52.6	11.4 0.217	46.5	10.7 0.229	38.6	8.1 0.210	47.5	11.9 0.251	45.0	9.6 0.215	29.2	7.6 0.261	44.4	10.2 0.228	42.7	8.9 0.208
		0.151										0.207								0.269		
2/18/80- 2/24/80 Snow pit	49.5	10.2 0.205	45.9	10.2 0.231	37.6	5.8 0.155	62.2	11.4 0.184	57.9	10.9 0.189	47.5	11.9 0.251	59.2	11.9 0.202	66.5	13.2 0.198	37.3	10.2 0.272	75.7	18.3 0.242	67.8	14.7 0.217
		0.248										0.209								0.245		
3/14/80- 3/16/80 Snow pit	77.0	19.0 0.247	52.0	12.7 0.241	49.5	10.9 0.220	77.5	19.0 0.246	71.1	16.8 0.256	66.5	13.5 0.202	71.9	18.3 0.254	56.6	17.0 0.300	37.6	10.2 0.270	50.0	12.2 0.244	60.4	12.7 0.210
		0.248										0.225								0.326		
3/18/80- 3/29/80 Snow pit	44.4	12.7 0.286	43.7	10.7 0.244	31.8	6.8 0.216	55.4	16.0 0.289	52.1	12.7 0.244	42.4	14.0 0.339	61.7	16.8 0.272								
		0.366										0.321										
4/7/80- 4/9/80 Snow pit	75.4	12.9 0.380	59.9	11.9 0.299	24.6	5.1 0.206	46.2	14.5 0.315	34.8	9.6 0.277	19.6	5.1 0.260	29.2	11.4 0.390	40.1	15.2 0.380	19.8	6.9 0.346	32.2	13.2 0.409	46.5	11.4 0.246
		0.410										0.420								0.420		
4/14/80- 4/15/80 Snow pit	15.7	3.5 0.270	27.2	9.6 0.355	17.5	3.8 0.221	36.8	12.7 0.345	17.8	4.5 0.245			24.9	9.1 0.367	31.2	10.2 0.325	10.9	3.0 0.275	22.5	8.9 0.398	27.9	7.1 0.235
																				0.420		

Table A4. Snow property data for Allagash. Additional data from site 1.

1977-1978					1978-1979					1979-1980				
Date	Depth (cm)	WE (cm)	Snow pit		Date	Depth (cm)	WE (cm)	Snow pit		Date	Depth (cm)	WE (cm)	Snow pit	
			Density (g/cm <sup>3</sup> )	Density (g/cm <sup>3</sup> )				Density (g/cm <sup>3</sup> )	density (g/cm <sup>3</sup> )				Density (g/cm <sup>3</sup> )	density (g/cm <sup>3</sup> )
12-27	40.6	5.3	0.131	--	12-04	19.6	3.6	0.184	0.180	12-24	12.7	2.5	0.197	0.144
01-12	36.1	7.9	0.207	0.220	12-11	18.0	2.5	0.141	0.180	12-31	28.4	4.6	0.161	0.140
01-17	54.1	9.9	0.183	0.197	12-18	55.1	7.1	0.129	0.138	01-14	20.3	9.6	0.473	0.240
01-23	78.2	19.0	0.244	--	01-01	64.0	13.2	0.206	0.244	01-21	22.1	5.3	0.241	0.180
01-31	74.4	14.5	0.195	0.208	01-08	61.5	18.3	0.297	0.231	01-28	34.8	6.6	0.190	0.186
02-06	66.5	14.5	0.218	0.214	01-15	71.1	19.8	0.279	0.231	02-04	54.8	6.9	0.197	0.242
02-20	75.7	21.1	0.278	0.235	01-22	90.9	22.4	0.246	0.232	02-18	36.3	6.4	0.175	0.235
02-27	73.7	21.6	0.293	0.264	02-05	86.4	22.1	0.256	0.291	02-25	52.1	11.4	0.219	0.246
03-06	78.2	23.6	0.302	0.296	02-12	77.5	20.8	0.269	0.245	03-03	48.8	9.6	0.198	0.246
03-13	78.0	23.9	0.306	0.269	02-19	74.4	21.1	0.283	0.238	03-10	63.0	12.4	0.198	0.228
03-27	115.6	36.3	0.314	0.257	03-05	78.2	24.6	0.315	0.331	03-17	71.1	17.3	0.243	0.261
04-03	111.0	36.1	0.325	0.312	03-12	67.8	17.8	0.262	0.274	03-24	69.1	14.7	0.213	0.264
					03-19	66.0	14.0	0.212	0.316	03-31	27.9	6.9	0.245	0.408
					03-26	31.8	14.7	0.464	0.460					
					04-01	53.3	14.0	0.262	0.256					
					04-16	53.8	19.8	0.368	0.400					
					04-23	16.5	8.1	0.493	0.460					

**APPENDIX B: METEOROLOGICAL AND HYDROLOGICAL DATA FOR  
THE UPPER SAINT JOHN RIVER BASIN,  
OCTOBER 1977 THROUGH MAY 1980**

**Stream Flow**

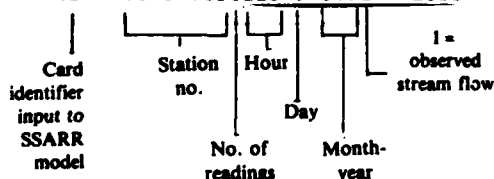
6C	010100008120	1	2781	2800	2650	2500	2400	2250	2100	2000	1950
6C	010100008120	9	2781	1850	1750	1680	1600	1550	1500	1450	1400
6D	01010000812017	2781	1350	1300	1250	1200	1150	1100	1070	1030	
6D	01010000412025	2781	1000	990	970	940	0	0	0	0	
6D	010100008120	1	3781	920	890	870	860	825	820	800	780
6D	010100008120	9	3781	765	750	735	725	710	690	680	675
6D	01010000812017	3781	670	660	650	640	630	630	640	665	
6D	01010000712025	3781	700	740	790	830	880	925	970	0	
6D	010100008120	1	4781	1000	990	970	940	920	890	870	850
6D	010100008120	9	4781	830	840	880	960	1100	1300	1500	1750
6D	01010000812017	4781	2100	2450	2900	3500	4250	5300	6600	7800	
6D	01010000612025	4781	9400	11500	12700	16400	18400	18900	0	0	
6D	010100008120	1	5781	16500	13300	11700	11200	11900	13900	16700	19000
6D	010100008120	9	5781	22100	26500	26400	23400	20200	18000	16100	14000
6D	01010000812017	5781	11800	9700	7740	6250	5410	6080	5110	3940	
6D	01010000712025	5781	3100	2530	2130	1800	1500	1230	1030	0	
6D	010105008120	1	2781	4400	3900	3500	3050	2800	2600	2350	2200
6D	010105008120	9	2781	2050	1950	1850	1760	1700	1650	1580	1520
6D	01010500812017	2781	1480	1420	1370	1310	1290	1260	1220	1190	
6D	01010500412025	2781	1160	1130	1110	1100	0	0	0	0	
6D	010105008120	1	3781	1070	1040	1030	1010	990	980	970	965
6D	010105008120	9	3781	945	935	920	910	900	895	885	880
6D	01010500812017	3781	875	870	865	860	855	850	850	860	880
6D	01010500712025	3781	940	1000	1100	1220	1480	1540	1700	0	
6D	010105008120	1	4781	1950	2050	2020	2000	1980	1920	1880	1830
6D	010105008120	9	4781	1800	1800	1880	2050	2300	2750	3200	3850
6D	01010500812017	4781	4500	5200	6300	7500	9500	12000	14000	17000	
6D	01010500612025	4781	20000	23100	26300	30000	36000	38200	0	0	
6D	010105008120	1	5781	33900	27500	23300	22900	24700	28900	34700	39300
6D	010105008120	9	5781	44800	55700	57000	51000	43800	39300	35800	31500
6D	01010500812017	5781	26100	22000	18100	14900	12900	13500	12400	9820	
6D	01010500712025	5781	7710	6200	5150	4340	3800	3270	2840	0	
6D	010110008120	1	2781	1610	1540	1480	1400	1330	1270	1220	1170
6D	010110008120	9	2781	1120	1080	1030	1000	970	950	920	890
6D	01011000812017	2781	860	840	810	790	770	750	730	710	
6D	01011000412025	2781	695	680	670	655	0	0	0	0	
6D	010110008120	1	3781	640	630	620	610	600	590	580	575
6D	010110008120	9	3781	565	555	550	545	540	535	530	525
6D	01011000812017	3781	520	515	510	510	505	500	500	505	510
6D	01011000712025	3781	520	545	580	625	670	740	790	0	
6D	010110008120	1	4781	850	900	920	905	890	875	860	850
6D	010110008120	9	4781	830	825	860	940	1050	1200	1350	1550
6D	01011000812017	4781	1800	2100	2450	2850	3400	4000	4600	5400	
6D	01011000612025	4781	6300	7500	8520	10200	11000	11700	0	0	
6D	010110008120	1	5781	10600	9150	8220	8110	8530	9600	11000	12100
6D	010110008120	9	5781	14000	16700	16400	14900	13300	12000	10800	9150
6D	01011000812017	5781	7500	6490	5810	5320	5170	5540	4760	4120	
6D	01011000712025	5781	3670	3290	2940	2630	2420	2220	2040	0	
6D	010100008120	1	2791	1400	1900	2300	1950	1640	1420	1250	1110
6D	010100008120	9	2791	1040	940	860	800	740	695	640	610
6D	01010000812017	2791	580	545	525	505	490	470	450	430	
6D	01010000412025	2791	420	410	400	385	0	0	0	0	
6D	010100008120	1	3791	380	370	365	360	375	490	660	1200
6D	010100008120	9	3791	2500	4700	5000	4500	4000	3650	3300	3100

St. John River at 9-Mile, 1978

St. John River at Dickey, 1978

Allagash River near Allagash, 1978

St. John River at 9-Mile, 1979



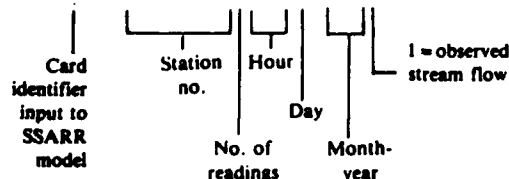


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6D	01010000712025	3791	4500	9000	13000	15300	14000	12100	10400	0
6D	010100008120 1	4791	10100	10300	9380	8470	7510	6350	5100	4420
6D	010100008120 9	4791	3870	3470	3070	2660	2730	3300	4570	5490
6D	01010000812017	4791	6390	6560	6720	6550	7610	9750	10300	12400
6D	01010000612025	4791	14600	17400	23600	31500	34200	30300	0	0
6D	010100008120 1	5791	23800	19100	15400	12700	10900	9030	7160	5760
6D	010100008120 9	5791	4980	5180	5000	4120	3410	3080	2700	2320
6D	01010000812017	5791	2020	1770	1520	1300	1130	1220	1660	1460
6D	01010000712025	5791	1250	3020	7260	7100	6600	7650	10900	0
6D	010105008120 1	2791	3050	3700	4490	4250	3700	3250	2850	2520
6D	010105008120 9	2791	2270	2100	1990	1850	1750	1680	1580	1490
6D	01010500812017	2791	1400	1300	1250	1200	1150	1100	1040	1000
6D	01010500412025	2791	960	920	880	850	0	0	0	0
6D	010105008120 1	3791	810	775	760	745	745	860	1180	1650
6D	010105008120 9	3791	4100	8500	10000	9500	9000	8200	7500	7000
6D	01010500812017	3791	6500	5900	5600	5100	4800	4500	4500	6200
6D	01010500712025	3791	12000	21000	29300	32000	31200	25500	21300	0
6D	010105008120 1	4791	19500	19500	18600	16500	15100	13000	10500	9230
6D	010105008120 9	4791	8330	7570	6520	6310	5720	6310	8290	10300
6D	01010500812017	4791	11800	12400	12500	12400	13500	17000	19200	22700
6D	01010500612025	4791	28400	34700	48000	68200	86800	80900	0	0
6D	010105008120 1	5791	60300	50000	38800	29900	24900	20600	16300	13100
6D	010105008120 9	5791	11300	11500	11800	9990	8200	7360	6750	5840
6D	01010500812017	5791	5140	4430	3830	3330	2920	2720	2970	3350
6D	01010500712025	5791	2990	3380	10100	13900	13900	17000	23700	0
6D	010110008120 1	2791	1820	1900	1900	1880	1790	1700	1630	1570
6D	010110008120 9	2791	1500	1400	1350	1300	1250	1200	1150	1110
6D	01011000812017	2791	1080	1020	1000	960	940	910	880	840
6D	01011000412025	2791	820	795	775	750	0	0	0	0
6D	010110008120 1	3791	740	720	705	700	710	760	945	1350
6D	010110008120 9	3791	2380	3400	3950	3900	3750	3480	3200	3000
6D	01011000812017	3791	2850	2630	2500	2400	2300	2210	2280	2480
6D	01011000712025	3791	3250	5450	12000	11600	9980	8600	7690	0
6D	010110008120 1	4791	7330	6940	6570	6170	5870	5540	5190	4780
6D	010110008120 9	4791	4500	4310	3990	3760	3570	3750	4080	4230
6D	01011000812017	4791	4480	4460	4430	4290	4480	5020	5320	6230
6D	01011000612025	4791	7240	9130	14100	20200	26700	25800	0	0
6D	010110008120 1	5791	21500	16600	12700	10200	8200	6800	5800	5200
6D	010110008120 9	5791	4750	4800	4900	4700	4200	3590	3050	2650
6D	01011000812017	5791	2300	2000	1800	1650	1550	1500	1550	1640
6D	01011000712025	5791	1660	1650	2000	3400	4500	5600	8000	0
6D	010100008120 1	2801	285	275	265	255	245	235	230	220
6D	010100008120 9	2801	210	205	195	190	180	175	170	165
6D	01010000812017	2801	160	155	150	145	140	140	135	130
6D	01010000512025	2801	130	125	125	125	125	0	0	0
6D	010100008120 1	3801	120	120	120	120	120	125	125	130
6D	010100008120 9	3801	130	130	135	140	140	145	150	155
6D	01010000812017	3801	160	170	185	205	230	260	295	340
6D	01010000712025	3801	380	430	480	530	560	590	650	0
6D	010100008120 1	4801	700	800	960	1300	1850	1860	1800	1750
6D	010100008120 9	4801	1800	1950	2500	4500	6600	10400	14400	15200
6D	01010000812017	4801	11600	8740	6220	5190	5430	5020	4370	4250
6D	01010000612025	4801	4880	5490	6720	8660	9120	6950	0	0
6D	010100008120 1	5801	6690	6180	5380	4560	3850	3260	2920	3170
6D	010100008120 9	5801	3440	3380	3100	2770	2560	2570	2910	2820
6D	01010000812017	5801	2480	2160	2610	4170	3630	2870	2350	2020
6D	01010000712025	5801	1750	1520	1340	1220	1120	1010	885	0

St. John River at Dickey, 1979

Allagash River near Allagash, 1979

St. John River at 9-Mile, 1980



6D	010105008120	1	2801	630	610	580	560	540	525	500	490
6D	010105008120	9	2801	470	460	450	430	420	410	395	385
6D	01010500812017	2801		380	365	355	345	340	335	330	325
6D	01010500512025	2801		320	315	310	310	305	0	0	0
6D	010105008120	1	3801	300	300	295	300	300	305	305	310
6D	010105008120	9	3801	310	315	320	325	330	345	355	370
6D	01010500812017	3801		385	425	470	525	600	680	760	850
6D	01010500712025	3801		950	1000	1100	1200	1250	1300	1400	0
6D	010105008120	1	4801	1500	1700	1900	2150	2750	3600	3750	3700
6D	010105008120	9	4801	3700	4050	5300	9000	14000	22500	29400	33700
6D	01010500812017	4801		26700	19100	13800	11000	10600	10100	8870	8440
6D	01010500612025	4801		9760	11300	12800	15900	16200	14200	0	0
6D	010105008120	1	5801	12700	12000	10700	9140	7730	6560	5870	6350
6D	010105008120	9	5801	7190	6900	6230	5590	5050	5200	5940	5950
6D	01010500812017	5801		5200	4600	4360	6060	7070	6140	5090	4240
6D	01010500712025	5801		3660	3190	2840	2590	2380	2190	2020	0
6D	010110008120	1	2801	380	380	375	370	365	365	360	360
6D	010110008120	9	2801	355	350	350	350	345	345	340	340
6D	01011000812017	2801		340	335	330	330	325	325	325	320
6D	01011000512025	2801		320	320	315	315	310	0	0	0
6D	010110008120	1	3801	310	305	305	300	300	305	305	305
6D	010110008120	9	3801	305	305	310	310	310	310	310	315
6D	01011000812017	3801		315	320	325	330	335	345	360	385
6D	01011000712025	3801		410	440	475	520	570	630	690	0
6D	010110008120	1	4801	760	850	950	1020	1120	1200	1300	1450
6D	010110008120	9	4801	1700	2100	2700	3700	5000	6300	7200	8610
6D	01011000812017	4801		6860	5740	4780	4200	4320	3630	3430	3480
6D	01011000612025	4801		3700	3890	4280	4520	4290	4070	0	0
6D	010110008120	1	5801	3910	3790	3610	3390	3130	2910	2790	2990
6D	010110008120	9	5801	3250	3280	3040	2770	2590	2770	3130	2860
6D	01011000812017	5801		2550	2350	2500	2720	2650	2530	2380	2230
6D	01011000712025	5801		2030	1830	1730	1610	1490	1410	1340	0

St. John River at Dickey, 1980

Allagash River near Allagash, 1980

Card  
identifier  
input to  
SSARR  
model

Station  
no.

Hour

Day

No. of  
readings

Month-  
year

1 = observed  
stream flow

# Wind Speed

4D	1 120 1 2798	34	34	47	34	58	69	34	22	58	34	47	11	34	58
4D	1 12015 2798	34	47	58	34	22	22	00	22	34	34	22	11	11	
4D	1 120 1 3798	11	22	22	11	11	22	00	22	11	11	22	69	22	47
4D	1 12015 3798	58	22	34	34	22	34	11	11	11	34	22	34	69	22
4D	1312029 3798	11	22	11											
4D	1 120 1 4798	34	22	11	22	22	11	58	22	00	34	69	58	34	22
4D	1 12015 4798	22	22	22	22	22	22	11	00	22	22	22	34	47	47
4D	1212029 4798	00	11												
4D	1 120 1 5798	58	47	22	11	58	114	81	22	47	69	22	69	34	00
4D	1 12015 5798	47	11	22	45	45	45	45	67	45	22	67	67	45	22
4D	1312029 5798	45	45	22											
4D	1 120 1 2808	47	34	34	22	34	11	11	11	11	22	11	11	47	47
4D	1 12015 2808	58	00	58	69	92	11	34	11	22	22	34	34	11	22
4D	1112029 2808	47													
4D	1 120 1 3808	58	22	11	34	22	47	34	11	11	22	47	69	11	34
4D	1 12015 3808	58	47	22	34	47	11	34	58	34	11	22	22	22	22
4D	1312029 3808	22	22	22											
4D	1 120 1 4808	11	22	22	34	22	22	69	47	34	58	11	47	34	
4D	1 12015 4808			47	47	34	47	58	69	58	47	11	22	22	00
4D	1212029 4808	22	00												
4D	1 120 1 5808	22	45	45	67	67	45	67	45	22	45	67	90	45	22
4D	1 12015 5808	22	47	22	47	34	22	58	47	22	34	34	47	47	22
4D	1312029 5808	34	22	22											

Card identifier input to SSARR model

Station no.

No. of readings/ card default = 14

Hour

Day

Year

Month

Code for wind speed (m/h xxx.x)

Wind speed (m/h)

# Rain Fall

4P	14120	7	2783	622120	9	3212014	8912027	95				
4P	15120	6	3783	9012014		47612019	5112020	9012021	546			
4P	1412022	3783		52412023		59112026	26012027	1556				
4P	1512011	4783		23512020		59712021	32412023	17112024	152			
4P	15120	1	5783	44120	8	89120	9	28612021	43812028	108		
4P	1212029	5783		8312031		235						
4P	15120	1	2793	260120	2	121120	3	1312021	1312022	70		
4P	1412024	2793		1912026		16512027	24112028	70				
4P	15120	2	3793	38120	6	267120	7	6312011	1312012	25		
4P	1512013	3793		11412025		22912026	36812027	1312029	19			
4P	1112031	3793		190								
4P	15120	1	4793	13120	2	140120	3	102120	5	190120	6	43
4P	15120	7	4793	46120	8	13120	9	7612010	40012011	19		
4P	1512023	4793		1912026		0612027		7012028	37512029	292		
4P	1112030	4793		13								
4P	15120	1	5793	546120	2	13120	4	76120	5	3212013	25	
4P	1512021	5793		5112025		42512026	26712027	1312028	292			
4P	1312029	5793		36812030		56512031	70					
4P	15120	5	2803	3212013		0612016	17812022	3812023	63			
4P	1212024	2803		1912025		32						
4P	15120	5	3803	63120	6	51120	7	06120	9	20312010	13	
4P	1512011	3803		25412012		7612014	25412015	17812017	102			
4P	1212018	3803		61012026		127						
4P	15120	4	4803	6312010		25412011	3812013	7612014	25			
4P	1512015	4803		30412020		14012022	3812023	6312024	13			
4P	1212026	4803		19012027		63						
4P	15120	7	5803	133120	8	133120	9	6312013	15912014	152		
4P	1312018	5803		6312018		6312019	15912031	32				

Card  
identifier  
input to  
SSARR  
model

Station  
no.

Hour

Day

Month

Year

Code for  
rain  
(in., xx.xx)

1st  
reading  
of  
rain

Day

Hour

2nd  
reading  
of  
rain

Day

Hour

3rd  
reading  
of  
rain

Day

Hour

4th  
reading  
of  
rain

Day

Hour

5th  
reading  
of  
rain

# Air Temperature

4D	1 120 1 2784	32	-40	-94	-58	-58	-31	158	86	59	-67	-31	122	68	-22
4D	1 12015 2784	248	131	86	185	68	50	104	194	167	158	122	266	257	140
4D	1 120 1 3784	122	176	59	95	50	122	158	149	140	158	158	266	158	248
4D	1 12015 3784	302	104	32	59	158	212	149	262	194	176	212	176	284	338
4D	1312029 3784	329	266	266	0	0	0	0	0	0	0	0	0	0	0
4D	1 120 1 4784	176	239	140	176	320	320	284	320	338	356	356	356	374	374
4D	1 12015 4784	347	374	347	363	337	411	344	337	352	363	374	374	392	392
4D	1212029 4784	392	292	0	0	0	0	0	0	0	0	0	0	0	0
4D	1 120 1 5784	320	401	392	383	410	410	428	464	410	500	482	509	516	509
4D	1 12015 5784	572	545	590	545	518	473	464	455	473	486	566	586	549	650
4D	1312029 5784	643	636	596	0	0	0	0	0	0	0	0	0	0	0
4D	1 120 1 2794	262	214	135	176	52	63	77	146	-63	-149	-140	-142	-130	-103
4D	1 12015 2794	-121	-110	-140	-85	-25	103	275	169	164	320	175	135	211	333
4D	1 120 1 3794	220	223	299	362	405	423	358	340	326	257	308	124	774	333
4D	1 12015 3794	149	70	103	283	310	351	409	421	463	446	380	353	221	225
4D	1312029 3794	297	362	356											
4D	1 120 1 4794	306	301	364	360	301	324	290	225	243	324	324	351	416	403
4D	1 12015 4794	353	515	335	311	385	445	515	506	423	425	443	576	526	562
4D	1212029 4794	515	513												
4D	1 120 1 5794	513	428	500	455	399	399	441	497	655	486	490	553	590	556
4D	1 12015 5794	610	596	704	576	652	635	655	488	526	569	493	463	576	529
4D	1312029 5794	540	560	569											
4D	1 120 1 2804	18	38	178	47	95	88	18	76	16	-23	26	97	31	77
4D	1 12015 2804	-40	32	45	74	232	223	227	11	101	72	145	-58	-13	31
4D	1112029 2804	-25													
4D	1 120 1 3804	7	-20	59	106	180	153	149	85	194	135	218	34	32	166
4D	1 12015 3804	135	88	90	245	250	124	230	295	360	279	326	346	333	300
4D	1312029 3804	382	326	290											
4D	1 120 1 4804	275	346	371	360	362	299	214	355	446	446	391	380	432	401
4D	1 12015 4804	470	401	301	335	310	365	387	245	346	391	466	445	416	391
4D	1212029 4804	416	472												
4D	1 120 1 5804	475	526	500	481	351	410	475	401	436	436	443	605	495	520
4D	1 12015 5804	430	475	466	515	605	481	517	590	490	486	520	455	452	461
4D	1312029 5804	446	486	590											

Card identifier input to SSARR model

Station no.

Hour

Day

Year

Code for air temperature (°F, xxx.x)

Air temperature readings

No. of readings/ card, default = 14

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Merry, Carolyn J.

Use of Landsat digital data for snow cover mapping in the Upper Saint John River Basin, Maine / Carolyn J. Merry and Michael S. Miller. Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1987.

v, 74 p., illus.; 28 cm. (CRREL Report 87-8.)

Bibliography: p. 52.

1. Hydrologic modeling. 2. Landsat. 3. Remote sensing. 4. Runoff. 5. Snow cover. 6. Snow water equivalent. I. Miller, Michael S. II. United States. Army. Corps of Engineers. III. Cold Regions Research and Engineering Laboratory, Hanover, N.H. IV. Series: CRREL Report 87-8.

END

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